REMARKS

Applicant thanks the Examiner for the very thorough consideration given the present application.

Claims 2-12 are now present in this application. Claims 2, 3, 4, 7 and 10 are independent. By this amendment, claim 1 has been canceled without prejudice, claims 2 and 3 have been re-written in independent form, and allowed claim 10 has been amended by changing "diagonal size" to - - diagonal size (U) - - to provide properly define the term "(U)" in the equation set forth in claim 10. No new matter is involved.

Reconsideration of this application, as amended, is respectfully requested.

Entry of Amendments

Applicant respectfully submits that it is proper to enter the claim amendments for a number of reasons. The Amendments to claims 1-3, i.e., canceling claim 1 and re-writing claims 2 and 3 in independent form, follow the suggestions of the Examiner to place claims 2 and 3 in condition for allowance. The amendment to claim 10 makes that claim consistent with the other claims and makes it clearer in that it defines the quantity (U) in the equation in that claim in the same manner in which it is defined in the other allowed claims.

Claim Objections

The Examiner continues to object to claims 1, 4, 7 and 10 because of several informalities. Applicant respectfully traverses this objection, which is moot with respect to claim 1, which has been canceled without prejudice.

The Office Action indicates that a natural log operation can only be performed on unitless numbers but, in the equations of these claims, the natural log of U is taken where U has units of millimeters. The Office Action also indicates that units are not provided for the constants added to either side of the inequalities and states that units are required for all constants, or variables appearing in an equation, except for multiplicative constants. The Office Action also indicates that if a constant or variable is unitless or treated as unitless in an equation, this must be indicated.

Applicant respectfully submits that logarithmic units are abstract mathematical units that can be used to express any quantities, physical or mathematical, that are defined on a logarithmic scale, i.e., as being proportional to the value of a logarithm function. Moreover, while the arguments of logarithmic (or trigonometric or exponential) functions are dimensionless, an absolute measurement of a length is also dimensionless in the sense that an absolute measurement of length is actually a comparison of a length value, e.g., 10 millimeters to a reference length, e.g., a millimeter. In this sense, the parameter "U" is dimensionless. A similar example is

measurement of angles in "degrees" or "radians", where these units are really the ratio of arc length to radius of an arc circle (2 pi radians is the ratio of the arc length of one quarter of a circle to its radius) and are, therefore, dimensionless.

Accordingly, Applicant respectfully submits that its disclosure is clear to one of ordinary skill in the art and does not need to be amended to indicate which parameters in its disclosed and/or claimed equations are unitless.

Turning to the mathematical expressions in the claims, three separate parts are set forth in each mathematical expression. Using claim 1 as an example, all three separate parts are unitless. The left hand part is given in terms of a natural logarithm, which is dimensionless. The middle part is given in terms of the product of dimensionless rations (Rh, Rv and Ro) divided by U, which is expressed in terms of a distance, and multiplied by Tc, which is expressed in terms of a distance – so that the resulting product is dimensionless. The right hand part, times the left hand part, is given in terms of a natural logarithm, which is dimensionless.

Moreover, Applicant does not supply units for the multiplying factors and added factors and subtracted factors in the equations recited in claims 1, 4, 7 and 10 because these are just mathematical number-type factors that have no units associated with them.

Applicant respectfully submits that the meaning of the equations in these claims is clear to one of ordinary skill in the art, who is expected to take the preceding explanation into consideration when reading the disclosure and claims.

Furthermore, Applicant is not limiting their equations to be determined in terms of millimeters or inches or other unit, as long as all of the dimensions are expressed in the same unit. Because of this, Applicant does not believe that it is necessary to recite a particular scale in its equations.

In response to the aforementioned arguments, the outstanding Office Action states that the natural logarithm is based on the transcendental mathematical constant e, where $e^y = x$ and concludes that because e does not have units, that neither x nor y can have units.

Applicant respectfully submits that the Examiner's position overlooks the fact that any parameter, whether it has units associated with it or not, can have its logarithm determined and can be expressed either as a unitless parameter or, to be characterized as having the same unit as the parameter whose logarithm is taken. In fact, Applicant respectfully submits that this characterization of a logarithm in terms of the units of the parameter whose logarithm is taken, is a common occurrence in all branches of science. In this regard, Applicant cites, and provides copies, of four references.

1. "What is Richter Magnitude?," a six page Internet article from www.seismo.unr.edu/ftp/pub/louie/class/100/magnitude.html, dated 9 October 1996.
2. " Kevin's logarithmic law for running," a four page Internet article from www.astro.washington.edu/kevin/runs.html, dated 17 August 1999.
3. "Personal and Outdoor Nitrogen Dioxide Concentrations in Relation to Degree of Urbanization and Traffic Density," a ten page article from ehp.niehs.gov/members/2001/suppl-3/411-417rijnders/rijnders-full.html, dated June 8, 2001.
4. "User Location Service over an 802.11 Ad-Hoc Network," by Li Song et al., 13 pages, undated.

The attached article entitled "What is Richter Magnitude," points out that Richter magnitude is found by taking the log to the base 10 of amplitude in millimeters. The attached article concerning Kevin's logarithmic law for running clearly graphs the logarithm of distance jogged (in miles). The article entitled "Personal and Outdoor Nitrogen Dioxide Concentrations in Relation to Degree of urbanization and Traffic Density" clearly points out the usefulness of determining distance to a nearby highway by using the logarithm of that distance because of the author's expectation of an exponential decay of nitrogen dioxide with increasing distance of a school from a road (page 3, last

paragraph of the Data Analysis section). The Song et al. article clearly plots signal strength with respect to the logarithm of distance, in meters, as a result of the authors' radio frequency (RF) model.

Is the Richter scale magnitude dimensionless or is it proper to express it in terms of a unit of length, as is done in the aforementioned article? Similarly, are the distances expressed in the other three cited articles properly characterized in terms of a unit length, as is done in those three articles?

Applicant respectfully submits that the mathematical expressions in its claims have three parts, each of which is expressed in terms of dimensionless quantities, and that fact is clear to one of ordinary skill in the art. As a result, Applicant respectfully submits that there is no need to modify the claimed invention in any manner whatsoever, let alone to indicate in the claims if a constant or variable is unitless or is treated as unitless. Applicant respectfully submits that one of ordinary skill in the art is well aware of the fact that parameters that logarithms can be used to express unitless parameters as well as parameters that have units and that one of ordinary skill in the art clearly understands the claimed invention in the dimensionless terms of each part of the mathematical expressions found in the claims.

The Office Action also indicates that the units that are used to calculate shape dramatically affect the shape of the claimed CRT panel and that the resulting panel is dependent on the units used to calculate the limits of the

inequality because a constant is added or subtracted from the natural logarithm of the diagonal length.

Initially, Applicants note that this is a new ground of objection that was not necessitated by Applicant's Amendment filed on December 7, 2005. In response to this new ground of objection, Applicant respectfully submits that, while one of ordinary skill in the art might not want to build a CRT with any possible dimensions, different systems of dimensions are related to one another by known conversion factors, so if a skilled worker wants to build a CRT with a faceplate having a Tc of 15 mm, for example, that 15 mm thickness can also be expressed as a decimal part of an inch or as a decimal part of a mile.

Accordingly, this objection is improper and should be withdrawn.

For the aforementioned reasons, Applicant respectfully submits that the objections to claims 1, 4, 7 and 10 have been overcome.

Reconsideration and withdrawal of these objections to claims 1, 4, 7 and 10 are respectfully requested.

Rejections under 35 U.S.C. § 103

Claim 1 stands rejected under 35 U.S.C. § 103(a) as being unpatentable over U.S. Patent 4,537,321 to Tokita in view of U.S. Published pending Patent Application 2003/0122474 and further in view of U.S. Patent 4,537,322 to Okada et al. ("Okada"). This rejection is respectfully traversed as moot because

claim 1 has been canceled.

Accordingly, reconsideration and withdrawal of this rejection of claim 1 are respectfully requested.

Allowed and Allowable Subject Matter

The Examiner states that claims 2 and 3 would be allowable if rewritten in independent form.

Applicant thanks the Examiner for the early indication of allowable subject matter in this application, and has re-written claims 2 and 3 in independent form to make them allowable.

Conclusion

All of the stated grounds of objection and rejection have been properly traversed, accommodated, or rendered moot. Applicant therefore respectfully requests that the Examiner reconsider all presently outstanding rejections and that they be withdrawn. It is believed that a full and complete response has been made to the outstanding Office Action, and as such, the present application is in condition for allowance.

If the Examiner believes, for any reason, that personal communication will expedite prosecution of this application, the Examiner is invited to telephone

Robert J. Webster, Registration No. 46,472, at (703) 205-8076, in the Washington, D.C. area.

Prompt and favorable consideration of this Amendment is respectfully requested.

If necessary, the Commissioner is hereby authorized in this, concurrent, and future replies, to charge payment or credit any overpayment to Deposit Account No. 02-2448 for any additional fees required under 37 C.F.R. §§ 1.16 or 1.17; particularly, extension of time fees.

Respectfully submitted,

BIRCH, STEWART, KOLASCH & BIRCH, LLP

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Attachment: Four References, cited above.

User Location Service over an 802.11 Ad-Hoc Network

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Abstract

User location service for context-aware applications in wireless network is of great academia and industry interest, many research efforts were spent on obtaining location information within wireless network. This paper presents a different approach of determining location information. The location information is obtained over an ad-hoc wireless network, using IEEE 802.11 protocol. A triangulation method is described based on an empirical radio propagation model. Evaluations of both the propagation model and the triangulation method are conducted with experiment data.

Keywords: User *location*, IEEE 802.11, ad-hoc wireless network, signal strength, peer-to-peer network

1. Introduction

User location service for context-aware applications is a very interesting research topic. With the location information, many applications can be built, such as location-sensitive content delivery, cooperative wireless routing and real-time roadmap. A lot of approaches have been exploited in recent years, including GPS, ultrasound, infrared ray, visible light, radio frequency, etc [5]. Among these physical mediums and techniques, realizing user location and tracking in a standard IEEE 802.11 wireless LAN interested us most. There are some good reasons for this preference. First, 802.11 wireless protocol is the most popular wireless protocol today and usually no additional hardware cost is needed for the location service. Second, unlike other wireless protocols, such as Bluetooth or infrared signal, 802.11 has a relative large cover range while the power consumption is reasonable.

IEEE 802.11 specification defines more than one way for communications [7]. The most commonly used way is called "managed" or "infrastructure" mode, where each user contacts access point (AP), a more powerful station, and usually fixed to its location. This is similar to the cell phone model, where each cell phone talks to base station rather than talk to each other directly.

In our work, however, we choose another mode, namely "Ad-Hoc". An Ad-Hoc wireless network does not require an AP to be present; every wireless station is treated equally, and they are free to communicate to each other. The reasons for us to choose Ad-Hoc network over the managed mode lie in the following. First, Ad-Hoc wireless network is cheap and flexible. It does not require dedicated APs, thus allows highly mobile stations to be present. In the environment where the infrastructure is not deployed yet, or is not convenient to be deployed, our approach is especially useful. Second, Ad-Hoc network fits better for certain location-sensitive wireless applications. One example is cooperative routing. Suppose a group of wireless stations need to forward packets by relaying, Ad-Hoc network will have a better performance since each wireless station can find the nearest station to talk to, this guarantees a higher transfer rate and low power assumption. Moreover, with the capability of talking to the neighbor wireless station and propagate the communications without requiring APs at present, Ad-Hoc networks potentially have a larger coverage and better adaptability than managed wireless network.

To the best of our knowledge, most of the previous researches on location service over 802.11 networks were focused on the environments with AP infrastructure [1][2][9][10][11]. While there are some research projects that try to provide ad-hoc location service, they all rely on their own hardware without utilizing the facilities that 802.11 provides [6][8].

In this paper, we investigate the problem of user location over an 802.11 Ad-Hoc network. The contribution of this paper could be summarized as follows:

- We analyze the various factors that could affect signal strengths in an 802.11 network in Ad-hoc mode. Based on our experiments, we argue that the effects of obstruction/orientation are so prominent that they should be modeled explicitly.
- We built a radio propagation model that could express the variance of obstruction/orientation. We also designed a new location algorithm that incorporates the guess of the degree of obstruction/orientation.
- We empirically trained our models and evaluated them by experiments. Our results give a rough picture of how well we can achieve in such a location service.

The rest of the paper is organized as follows. Section 2 explains the previous research related to our work. In section 3, we introduce the general idea of our approach in high level. Our main work is described in section 4, including the analysis of various factors, the models used in determining locations, and the evaluation of the models. Finally we discuss some possible future research directions and conclude the paper in section 5.

2. Related Work

In recent years, some systems by both industry and academia researchers were built to provide location information in a RF (Radio Frequency) network. Although different variables are used to estimate the distance, e.g. packet loss, byte corruption, it is commonly recognized that signal strength is potentially the best indicator for measuring distance [8]. While signal strength is widely used, different approaches are used in different scenarios. Basically, these systems could be classified into two classes.

The first class, characterized by RADAR [1][2], which was developed in Microsoft Research, built their system on general-purpose data networks, mostly on the 802.11b LAN. They used some proximity techniques as basic method, even though the detailed configurations are various. RADAR is a building-wide location and tracking system. In RADAR, the signal strength is measured when transmitting beacon packet between the mobile host and AP. Prior to the real-time localization, RADAR needs to build up a radio map for the area interested by doing random or uniform sampling in that area. After that the location information is computed by searching the nearest neighbor of the measured signal strength within the radio map. Usually, at least 3 APs are used to carry out the communication task with the mobile host and at the same time they act as the fixed location reference points. In the latest report on RADAR, more advanced techniques such as continuous user tracking and environment profiling are adopted to get more precise location information in a dynamic environment. Note that besides the basic radio map approach, RADAR also tried the triangulation approach based on some in-door radio propagation model. However, the result shows that the triangulation does not work as well as radio map in their scenario. Similar approaches are also used in the projects at CMU [11], Rice [9], and other places [10]. The statistic approaches used in these projects are quite different, e.g. a neural network based model was tried in [11] but with poor performance, and Bayesian Network and Hidden Markov Model are used in [9].

Our project differs form these systems in a fundamental aspect that all these systems works in AP scenario while ours is applicable to the peer-to-peer mode. This difference makes the radio-map method impractical in our project, so we mainly focus on the direction of triangulation.

The second class, location services in ad-hoc wireless networks, has also been done in some projects. Two well-known examples are network sensors (motes) at UC Berkeley [8] and SpotON [6] at UW. Both of them built their location system on peer-to-peer networks without central control. But their work is based on their own hardware and communication protocols. Thus it is hard for others to repeat their experiments or use their techniques in real applications. In contrast, our system is based on 802.11, thus our techniques can be easily used in real applications without the support of specific platform. As to the data processing approach, [8] uses a log-distance path loss model to infer distance from signal strength, which is similar to our first model described in section 4.3. And our experiment shows that such a model is not adequate in our application.

3. Methodology

3.1 Triangulation approach in outdoor scenario

Our focus in this project has been put on using triangulation to provide location information in outdoor situations. As we have discussed in introduction, the location service in 802.11 network running in ad-hoc mode has both practical future and research challenge. This is the basic reason why we choose to solve location problem in ad-hoc mode, and on the other hand this decision also determines the method we will adopt and the scenario we will apply our method into. The ad-hoc mode makes the approach of building an offline database and conducting classification based on the training data, as did in RADAR[1][2] and other projects [10], not appropriate. The first reason is that we absolutely don't want to restrict our ad-hoc wireless network only within some areas where we have collected data and built up radio map. For most situations where the AP mode is replaced by ad-hoc mode, there must be some hindrance to deploying AP infrastructure, such as mobility requirement or lack of power supply, etc. In other words, most situations where 802.11 network is running in ad-hoc mode are those in temporary use. And thus building up a radio map in first place is obviously not reasonable for such situation. The second reason is that unlike in the infrastructure mode where some powerful workstations can be connected to the AP for storing data and computing, there are no AP and powerful computing units in ad-hoc networks. Thus storing a huge training database and perform classification may be infeasible. Therefore, we adopt the approach of building theoretical radio propagation model and using triangulation to accomplish localization.

Our early experiment shows, on one hand, the reverse proportional trend between the signal strength and the logarithm of distance, and on the other hand, the unpredictable and noisy nature of measured signal strength. Figure 1 is the signal strength we collected in out door scenario. From that we can see the obvious linear relation between signal strength and logarithm of distance. The reason of using logarithm of distance instead of direct meters in x-axis comes from the RF propagation model, which we will describe in section 4.3. However, the indoor situation is much more complex because of the radio reflection, diffusion and absorbance. This can be observed from Figure 2, where the data collected at hallway and two classrooms in EE building respectively. We see the saw-teeth shape in hallway data that means at 30 meters distance, the signal strength is even stronger than that in 20 meters. As for the data in classroom, the lines for EE037 and EE042 are quite different. These phenomena indicate that the

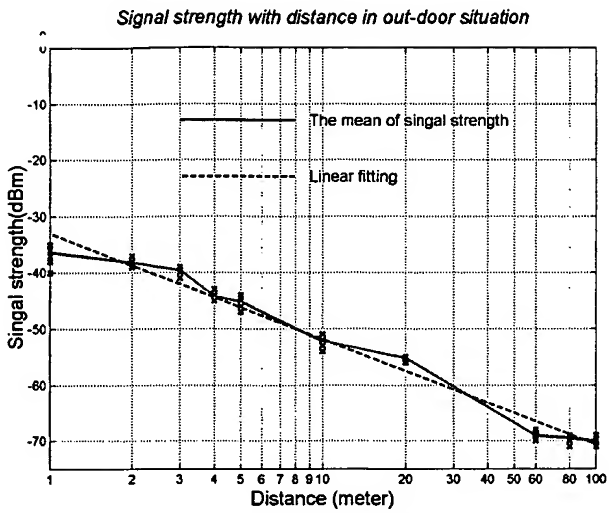

Figure 1. Outdoor situation

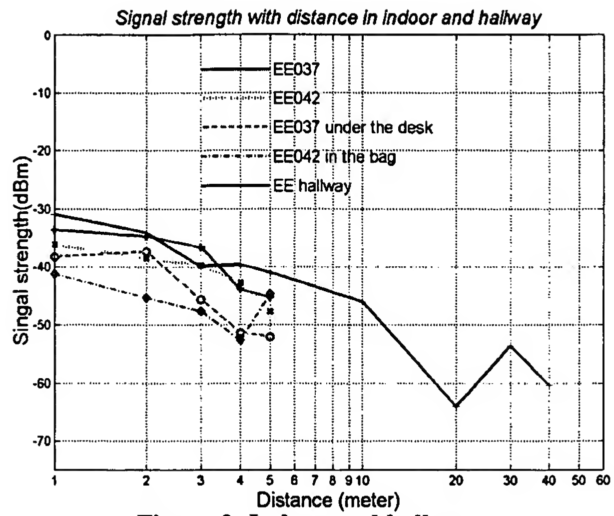

Figure 2. Indoor and hallway

indoor signal propagation is dominantly decided by some factors, mainly some constructional reason, other than distance. To initiate our work without facing too much intractable complexity, we start from the outdoor scenario, where the unpredictable factors are relatively less and stable. But it soon turns out that even for the seemingly simple outdoor situation, the data is still noisy and need to pay a lot of effort to get acceptable location information.

3.2 Description of General approach:

In this section we describe the general methodology we used in attacking this problem. We progressed our project in three steps one by one:

- First of all, we tried to screen out the principal factors which affect the signal strength dominantly by a serial of experiments. Unlike the radio map approach which does not require considering various factors explicitly and just did training and classification empirically, we have to take various factors into account to work out a computable RF propagation model with acceptable precision. In theory, numerous factors may affect the signal strength besides distance, some of them are fatal but hard to compute such as hardware, some of them are important and could not be neglected, such as obstructions, and some others only have minor affect and could be omitted for simplicity, such as power. In section 4.2, we describe in detail about how we differentiated those factors and screened out the principal factors.

- With the principal factors from first step in place, we designed our RF propagation model, which takes distance and obstructions as variables. There are also some parameters in this model need to be determined before this model could be used in triangulation. For this reason, we conducted some experiments to collect training data and then determine those parameters by training the model. This part is explained thoroughly in section 4.3.

- The last step is to verify our model by feeding it with real data to it and comparing the result with the actual value. We conduct another experiment to collect verifying data to make sure the verifying data is completely independent with the training data. We compute the result with both the models of taking obstruction in account and not. The

result shows that considering obstruction factor in propagation model will improve the precision of estimated location significantly. More descriptions and graphs for this step are in section 4.4.

In this paper, we made several assumptions to our scenario.

- Our approach is only applied to an outdoor environment without buildings, forests, etc among the peers. This means the effects of reflection and diffraction could be ignored and the main obstructions are human bodies.
- The peers work collaboratively and uniformly. For example, all the subjects need to hold their PDAs in front of chest (not in their bags) and there are no issues of security or privacy taken into account.

4. Experiments

4.1 Test bed

Our work is done on several *ipaq* i3800 PDAs over which we run *familiar 0.4* whose linux kernel version is 2.4. The working mode of the wireless device could be changed to Ad-Hoc by simply modifying the configuration file of */etc/pcmcia/wireless.opts*. There is a wireless extension toolkit named *iwconfig*, coming with the Linux installation for the *ipaq*. This toolkit contains some convenient tools to configure and monitor the wireless device working on *ipaq*, among which the most useful two are *iwconfig* and *iwspy*. The former one is used to configure most options of wireless device and the latter could be used to monitor the status of any other wireless peer in the Ad-Hoc network. The *iwspy* could isolate the signal strength of any specific peer in the network from others. Put it to another way, the strength measured for a peer is only caused by that peer regardless the existence of other peers. We use APIs provided in *iwlib* to write a data collector using C language that works similar to *iwspy* but with more control on data collection and recording. In all of our experiments, we use shell script calling this collector to get collect data.

The experiment is conducted in a wide flat parking lot, because there is no obstruction nearby and thus the effect of reflection is minimized. We made grid coordinates on the ground to locate each measured point. In our experiments, there are two roles. One role is called target, who is the peer that needs to be located. Another role is reference point, whose location is publicly known and who gather signal strength from the target and cooperate with other reference points in estimating the location of the target. For each measurement, 10 consecutive readings were made in 10 seconds interval to averaging the data and filtering out the randomized noise.

4.2 Discuss various factors

To build RF propagation model, we need to filter out various factors which will affect signal strength in various degrees. We did this work in two steps: First, we list all the possible factors that may affect signal strengths and we classify them into 4 different categories.

- The first category includes those factors that are fatal to the signal strength but usually not change in our scenario. This class includes hardware, the antenna height, radio frequency, etc. The literature shows these parameters are crucial in deciding the signal strength; however, since these factors are relatively stable in our scenario, we model their effect as constants.
- The second category is those factors that may change in our scenario and their changes cannot be ignored for us to predict the distance within an acceptable error range. Basically the obstructions/orientations are the factors we mainly considered in this category. Figure 3 shows the data measured outdoor when two people held the PDA

before their chest and did some rotation. In this experiment, the target PDA is always to the north of the measuring PDA. In Figure 3, S-N means the target PDA is facing south and measuring PDA is facing north, so in fact they were face-to-face then. In this case there is no obstruction between them. From Figure 3 we have the observation that the orientation is much more crucial than distance in affecting the propagation of signal. To make it more intuitive, the signal strength at 5 meters apart for back-to-back orientation is equal to 40 meters apart for face-to-back and 100 meters apart for face-to-face. And more precisely, contrasting to RADAR[1], we believe the real crucial factor is the obstruction formed by the PDA holder's body, but not the orientation itself. For example, our experiment shows in the case where one holder raising the PDA above head and thus no body obstruction formed there is only 3dBm fluctuation in different orientation, while with PDA before chest, the fluctuation is around 10dBm.

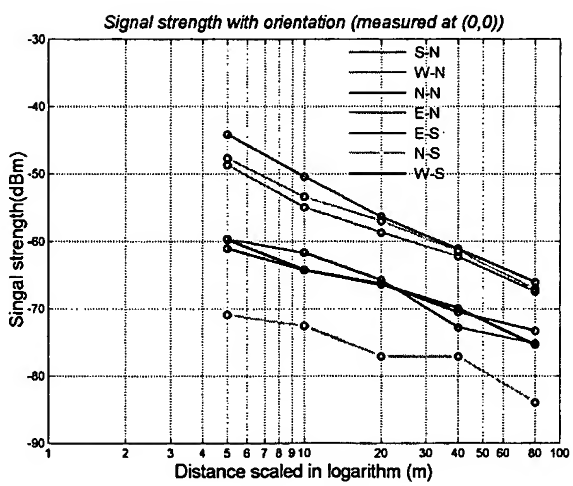

Figure3 Signal strength with orientations

- The third category includes those factors whose effects are obviously weaker than distances, such as power status of PDA, time of a day, weather, different PDA holder, etc. In our model, we ignore all factors in this category.

The last possible factor is random noise. In our approach, we compute average signal strength based on multiple samples to alleviate its effect.

4.3 Radio Propagation Model

4.3.1 Model Description

In our approach, one central task is to build a model describing the relation between signal strength and distance. Such a model is called radio propagation model in literature. Much work has been done in this area for both indoor and outdoor environments. But since we have some special requirements, we cannot find a model ready for use. For example, 802.11 works around the frequency of 2.4G, while most models are only valid for lower frequencies. We also require the distance between the sender and receiver is under 200m, which is the working range of 802.11, and the antenna height is around 1.5m, etc. Our strategy is referring to some general theoretical model, and then training the parameters and making some modifications based on our experiments. We consider two models for our application.

The first is the well-recognized log-distance path loss model. Both theoretical and measurement based models indicate that received signal power decreases logarithmically with distance, no matter indoor or outdoor [3][4]. The model can be described by:

$$P(d)(dBm) = P(d_0)(dBm) - 10\gamma \log(d / d_0) \quad (1)$$

Where P(d) is the signal power (strength) when sender and receiver are separated by a distance d; P(d0) is the signal strength at some reference distance d0, here we let d0=1m. γ is the path loss exponent, which indicates the rate at which the path loss increases with distance. The value of P(d0) depends on the specific hardware, the antenna height, transmission power, etc. The value of γ may be affected by the reflection, diffraction, air temperature, etc. This model does not express the effect of obstruction

and orientation explicitly, instead, their effects are reflected in the $P(d_0)$ and γ implicitly. $P(d_0)$ and γ are treated as constants and determined empirically.

As we have shown, obstructions and orientation contribute a lot to the signal loss and their effects vary significantly in different cases. Unlike the first model that treats the effects of obstructions and orientations as constants, our second model can express the variance of obstructions/orientations. We do it by adding one item to the first model and our new model then becomes:

$$P(d)(dBm) = P'(d_0)(dBm) - 10\gamma' \log(d/d_0) - n * HAF \quad (2)$$

The last item of this model characterizes the effects of humans obstructing the path between sender and receiver. Here n is the number of obstructions, which may take a decimal value. Based on the assumptions of our scenario, human bodies are the main barriers. HAF stands for Human Attenuation Factor, which value intuitively means the amount of signal that can be blocked by a single person. Our model is very similar to the Floor Attenuation Factor propagation model used in the Radar project [1]. Their model was used indoor and a Wall Attenuation Factor was introduced. In our approach, we ignore the difference of HAF from person to person. The value of HAF is thus considered constant whose value is determined by experiments. Note the values of $P'(d_0)$ and γ' in the second model are different from the values of $P(d_0)$ and γ in the first model, though they have the same physical meaning. The reason is that the effects of obstructions/orientations have been extracted from them and expressed separately.

4.3.2 Discussion of n

The variable of n in the second model plays an important role in our approach, whose value is determined at each measuring time. The first phenomena we observed is that other humans (neither sender or receiver) not very close to the sender or receiver (more than 10m away) will not affect the signal strength significantly, even if it's in the line-of-sight. The experiment is like this: while the sender and receiver stood 40m apart with face to face, we measure the signal strength in three situations respectively: 1) No people stand in between 2) A person stands 10m away from the sender in the line-of-sight 3) A person stands 20m away from the sender in the line-of-sight. The result is shown in Table 1.

	Signal Strength (dBm)
1st Case: no person in between	-59.8
2nd Case: a person 10m away	-61.0
3rd Case: a person 20m away	-60.2

Table 1. Effects of human on signal strength at different distances

Thus, the main obstructions in our scenario are the bodies of the sender and receiver. We further suppose each subject holds the PDAs in front of his chest, therefore the obstruction number n is only determined by the orientations of the sender and the receiver. The values of n in some special cases are shown in Figure 5 (a)-(e). In general, we can compute n from the orientations of the sender and the receiver using the formula:

$$n = (\alpha + \beta)/\pi \qquad (3)$$

where α, β are the radians of the orientations from the line-of-sight, as shown in Figure 5 (f). For simplicity, in our experiment the domain of n is the list {0, 0.5, 1, 1.5, 2} and the n computed using the formula will be rounded to nearest value in the domain. For example, if α=1, β=2, then from the formula, we get n=0.955, and approximately n=1.

4.3.3 Parameter Determination

Several parameters need to be determined empirically. In the first model they are $P(d_0)$, γ and in the second model

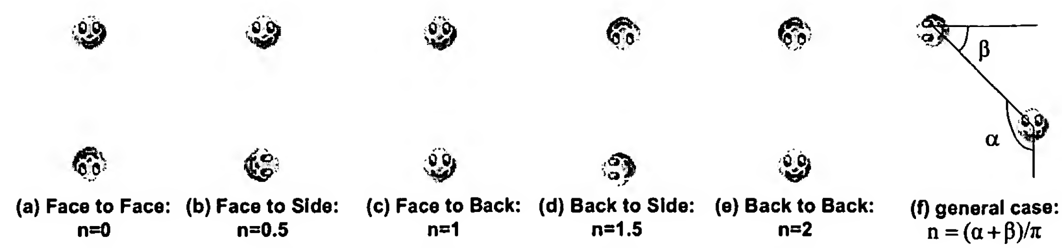

Figure 5. Computation of n from orientations

they are P'(d_0), γ' and HAF. To train these parameters, we measured the signal strength at different distances. And at each distance, we repeated the measurements for different orientations (i.e., different values of n).

To determine P(d_0) and γ for the first model, we draw the graph of the average signal strength across various orientations at each distance versus the log scale of distance. Thus we can get P(d_0) and γ by simple linear regression. As shown in blue line of Figure 6, we get P(d_0)= -49.35 and γ=1.17.

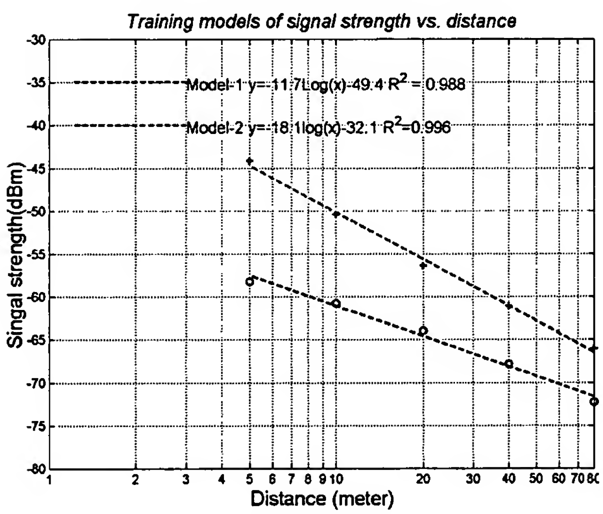

Figure 6. Signal Strength vs. Distance (log scale) for training P(d_0) and γ

To determine P'(d_0) and γ' for the second model, the data used is a little different. That is, at each distance, we only use the signal strength data when the two subjects are face to face. In that case, there is no obstruction and n=0. Then P'(d_0) and γ' can be determined using linear regression. We get P'(d_0)=-32.06 and γ'=1.81, as shown in the red line of Figure 6. Note in the Figure 6, R^2 is the coefficients of determination, which is the measurement of the goodness of the regression. The value of R^2 is from 0 to 1 and the higher value of it (closer to 1) the better of the regression. The pretty high values of R^2 in both models mean that there is a good match between the linear model and the real data.

The last parameter is HAF in the second model. At each distance, we draw the graph of signal strength versus n (the values of n are determined using the approach described in 4.3.2). Then we use linear regression and get the HAF for that distance, as shown in Figure 7. Finally we take the average value of HAF across all the distances and get HAF=10.40.

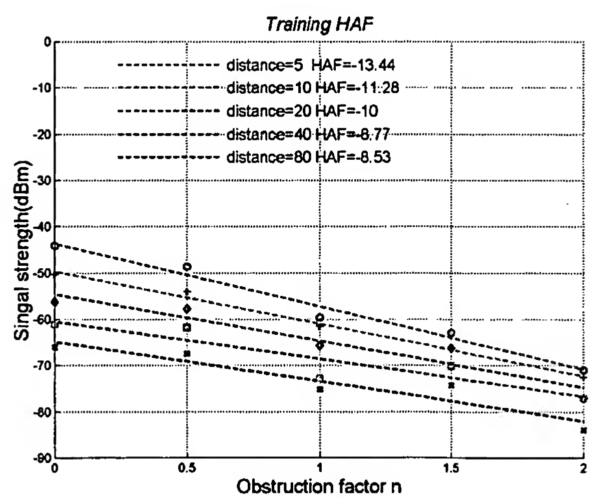

Figure 7. Signal Strength vs. n at different distances

Substituting the values of parameters, the two models for our scenario are:

1st model: $P(d)(dBm) = -49.35 - 11.7 * \log(d)$ (4)

2nd model:

$P(d)(dBm) = -32.06 - 18.1 * \log(d) - 10.40 * n$ (5)

4.4 Location Algorithms

Given the radio propagation model, we then describe our algorithms for location. For the first radio propagation model, the location approach is straightforward: we can determine the distance from signal strengths and locate subjects using a standard triangulation algorithm.

For the second model, we considered two cases. The simpler case supposes we can obtain the value of n through some way. This is possible in some scenarios. For example, a person A may know the rough direction of another person B relative to A and the orientation of B, e.g. B is walking northward. By that information, A can simply estimate the value of n. Note that we don't need exact data to compute n since the granularity of n in our approach is pretty coarse. After the estimation of n, the location using the second model is also straightforward.

In a more complex case, we have no other information to estimate n. The idea in this case is that first we guess n and we do triangulation for each guess of n; after we get the location based on the guess, we filter out those locations that are inconsistent with the guess; finally from all the consistent locations we take the result nearest to our measurement data. This is feasible because n can only take value from the list of {0, 0.5, 1, 1.5, 2}. We also need to guess the orientation of the subject being located, which could be north, east, south or west. Our algorithm is described in Figure 8. Note we need at least 3 reference points. We use two points with strongest signal strengths to compute the location candidate list and use the third point to select the nearest candidate. The reason is that usually the stronger signal strength, the higher quality the signal.

A, B, C are three reference points whose locations and orientations are publicly known as (x_a, y_a), (x_b, y_b) and (x_c, y_c). Also they can exchange their measurement information. D is the subject need to be located.

A, B, C measures the signal strength of D and exchange their measurements
From 3 the measurements we choose 2 with strongest signal strengths. Let A, B be the two points with the strongest signal strengths.

//Guess the obstruction numbers n_a, n_b
For n_a from {0, 0.5, 1, 1.5, 2}
    For n_b from {0, 0.5, 1, 1.5, 2}
        Locate D for the given n_a, n_b, i.e, get (x_d, y_d) using triangulation
        Choose the orientation of D that is consistent with the (x_d, y_d), n_a and n_b, i.e. satisfying the formula (3)
        If such a orientation exists
            Add the consistent solution $(x_d, y_d$, orientation) to the candidate list
        Else
            Continue
        End if
    Next n_b
Next n_a

//Choose the result from the candidate list
For each solution in candidate list, compute n_c and then the signal strength at reference point C. Choose the solution that is closest to the real measurement

Figure 8. Algorithm of location using the 2nd model and no prior knowledge

4.5 Evaluation

To evaluate our approach, we use a separated data set from the one used to train the parameters. Based on the test data, we want to answer two questions. The first

question is what kind of precision can be achieved when using signal strength to estimate distance. The second question is whether it is feasible to accomplish ad hoc localization using triangulation.

To answer the first question, we use the two models described in section 4.3 to estimate the distance. For the first model, no other information but signal strength is needed. For the second model, suppose we have estimated the obstruction number n through some way (in our experiment, we manually feed the n). Unlike previous work, we use relative error as the metric, as shown in (6).

$$e_r \equiv e / d_0 \equiv |d - d_0| / d_0 \quad (6)$$

where e_r is relative error, e is absolute error, d_0 is the real distance and d is the distance estimation. This makes more sense because the absolute error goes up obviously with the increasing of distance. Thus the absolute error in an experiment heavily depends on the sample distribution. In contrast, the relative error does not have obvious correlation with distance. The result is shown in Figure 9.

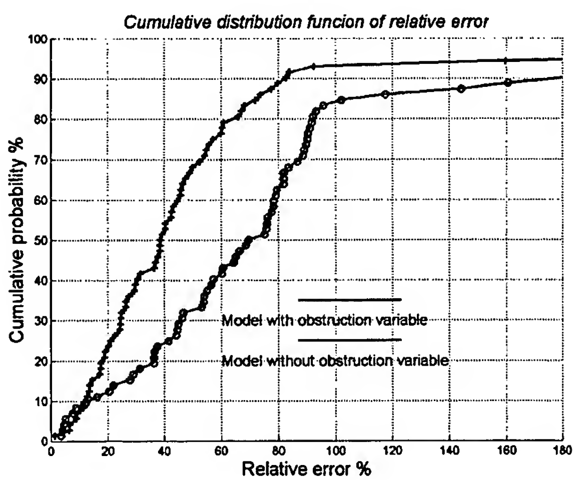

Figure 9. Cumulative Probability Function of relative errors in both models

In the graph, the red line and blue line represents the CPF of the 1st model and 2nd model, respectively. Consider the median (50th percentile), the 1st model provides a resolution of about 70% (relative error), and the 2nd model's resolution is nearly 40%. Also for the 20th percentile and 80th percentile, the 2nd model's relative error is almost half of that of the 1st model. Thus, we conclude that the explicit model of obstructions/orientations in the second model offers great help on reducing the relative errors in propagation models.

One may argue that this is not a fair comparison since we feed the obstruction information to the second model while the first model does not utilize this information. In our next evaluation, we use both models to do location by triangulation. For the first model, we use the standard triangulation algorithm. For the second model, we use the algorithm presented in section 4.4. Note that in such an evaluation, both models only need the signal strength data and the prior knowledge of obstructions are not necessary. The result could also be used to answer the second question: the feasibility of ad hoc location.

In our experiments, we found that a number of samples cannot be located using triangulation since the errors are so prominent that the triangulation relation does not hold any more. This is explained in Figure 10.

Thus besides relative error, we introduce another metric called location ratio, which is defined in (7)

$$LocationRatio \equiv \frac{NumberOfSamplesLocated}{TotalNumberOfSamples} \quad (7)$$

Thus, the relative error in this experiment is computed based only on those samples being located.

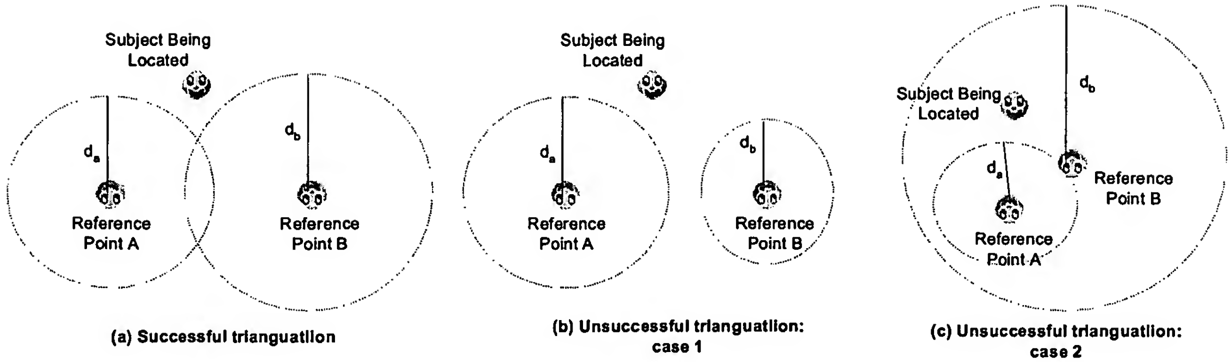

Figure 10. Successful Triangulation vs. Unsuccessful Triangulation (d_a and d_b stand for the distance estimations at point A and B respectively)

We use 24 samples in this experiment and the result is shown in Table 2

	Location Ratio	Relative Error
Location using first model	5/24=20.8%	34%
Location using second model	15/24=62.5%	39%

Table 2. Location Ratio and Relative Error in both models

From Table 2, we can have a general picture of how well our location service can be.

Without considering obstructions explicitly, only 20% times the target can be located using the signal strengths collected at each reference point. But with the 2nd model we presented in this paper, the location success rate increase to above 60%. If a target can be located, the relative errors are around 40% for both models.

Whether such a location service is useful or not depends on specific applications. Our conclusion here is that in our scenario, our model with obstruction factor n could offer much better successful location rate.

5 Discussion and Future work

5.1 Conclusion

From the data and analysis above we would like to point out that, even though our experiments indicate providing location information in Ad-Hoc wireless network is feasible, it is very hard to obtain location information of higher accuracy. The reasons are:

- There are many factors, together with distance, that dominant the signal strength. These factors include, but not limited to, obstructions, reflection, diffusion, hardware and so on. In our experiments, we noticed that at one certain location in the parking lot, the face-to-face signal strength is not the strongest one, and this would happen with a fairly high probability. This indicates that other factors are affecting the signal strength significantly.
- In the radio propagation models, the significance of distance is the logarithm of the actual distance. And at the same time, it is very hard to measure the non-log items precisely. For example, the item of obstruction factor in our model has a linear relation with the signal strength and we are only able to estimate it roughly. Thus, errors will be amplified exponentially on the result distance.
- The software and hardware we used for our experiment are not dedicated for measuring distance. Even though we looked into the source code of *iwspy* and

figured out the control detail of the wv_lan interface, the actual wireless card driver is beyond our control. The signal strength obtained from the driver is the statistic data over a certain period of time, rather than real-time data. More accurate results might be achieved with hardware dedicated for signal strength and a more friendly driver.

Despite the difficulties, our data indicate useful location information can be obtained in relatively simple environments. Next, We'd like to discuss the possible future work in this topic.

5.2 Random noise

We tried to use average to alleviate random noise occurred on experiment data – for each location the data is collected more than 10 times, and their average is used as the actual data. This proved to be effective for most cases, but not all cases. We noticed several groups of data are abnormal, several consecutive data would either be uniformly higher or lower than other data in the same group. This means that sometimes the random noise, e.g. a passing car, may have significant impact on signal noise and is not easily smoothed using average over a short period of time. We believe special hardware that reads real-time data would have a better chance to explain the nature of the noise.

5.3 Location propagation to other peers.

In our approach, a user could be located by 3 reference points who claim providing location service. In fact, after this user is located, he could also work as a reference point. Thus the location service could be propagated. This is pretty cool because that is a big advantage of ad-hoc network over centralized infrastructure. But since the location service will definitely introduce errors, the credibility of a new reference point will be lower than the original ones. In real P2P wireless networks, this brings an interesting question: should a user trust the original reference points far away whose locations are pretty precise but the signal strength is weak, or should the user trust a nearby new reference point whose location is not so trustable?

We believe this depends on the speed of precision loss during the location propagation. Clearly, there exists a tradeoff and more experiments are necessary for examine the tradeoff.

5.4 Light-weight location service.

Our current technique of getting signal strength is using *iwspy*, which requires pinging other peers to update the signal strength stored in the driver. This disturbs the network with unnecessary traffic and wastes power. According to the IEEE 802.11 specification [7], in an 802.11 ad-hoc network, one peer needs to publish synchronization packets at some interval in order to keep all peers synchronized. The random mechanism of choosing the publisher in fact guarantees all the peers be able to broadcast packets to others. Therefore we can collect the signal strength of these packets without flooding the network. In other words, signal strength could be collected as a natural by-product of wireless card's routine. To do that, *iwspy* is not adequate. We need to monitor the packets at a driver level.

5.5 Dynamic location

In this paper, we only investigate the problem of locating static users. Another interesting topic is how to handle moving users. The property of users' moving can help to provide better location information. The most commonly used property is that users' location should be continuous (close enough) from one sample time to the next sample time. This is helpful when the system cannot decide the exact location of a user from one group of data. For example, suppose at sample time 1 the system decides a user's possible locations can be l1 and l2,

which are pretty far away from each other, but of similar possibility, then at the next sample time 2, the system will get a new group of data, which will also provide new location information l3 and l4. Then from the 2 sets of possible locations, we could pick 2 nearest ones as the most likely location of the user.

5.6 Environment-aware profile.

In our approach, the location resolution depends on the values of parameters. Thus, a set of parameters trained in one environment may introduce errors when it is applied to another environment. To get accurate location information, the system should be aware of different environments, and use different parameters of the model. There are two approaches to do that. One way is building a parameter database and let the end users to switch between the parameter sets. Another way is let the reference points measure the signal strength of each other and train the parameters on the fly.

Acknowledgements:

We appreciate a lot to Ling Zhu and Tian Sang for helping us conducting the experiments. We also would like to thank Harlan Hile and Jonathan Ko for helping us make iwspy work and Evan Welbourne, Tal Shaked, Stanley Kok for sharing Ipaq with us.

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Personal and Outdoor Nitrogen Dioxide Concentrations in Relation to Degree of Urbanization and Traffic Density

Esther Rijnders, Nicole A.H. Janssen, Patricia H.N. van Vliet, and Bert Brunekreef

Abstract

To assess differences in exposure to air pollution from traffic in relation to degree of urbanization and traffic density, we measured personal and home outdoor nitrogen dioxide (NO_2) concentrations for 241 children from six different primary schools in the Netherlands. Three schools were situated in areas with varying degrees of urbanization (very urban, fairly urban, and nonurban) and three other schools were located near highways with varying traffic density (very busy, fairly busy, and not busy). Weekly averaged measurements were conducted during four different seasons. Simultaneously, indoor and outdoor measurements were conducted at the schools. Personal and outdoor NO_2 concentrations differed significantly among children attending schools in areas with different degrees of urbanization and among children attending schools in areas close to highways with different traffic densities. For the children living near highways, personal and outdoor NO_2 concentrations also significantly decreased with increasing distance of the home address to the highway. Differences in personal exposures between children from the different schools remained present and significant after adjusting for indoor sources of NO_2. This study has shown that personal and outdoor NO_2 concentrations are influenced significantly by the degree of urbanization of the city district and by the traffic density of and distance to a nearby highway. Because NO_2 can be considered a marker for air pollution from traffic, the more easily measured variables degree of urbanization, traffic density, and distance to a nearby highway can all be used to estimate exposure to traffic-related air pollution. *Key words:* distance, exposure, highways, nitrogen dioxide, traffic, urbanization. -- *Environ Health Perspect* 109(suppl 3):411-417 (2001).

http://ehpnet1.niehs.nih.gov/docs/2001/suppl-3/411-417rijnders/abstract.html

During the last decade, air pollution in relation to respiratory health has again become an important issue. In addition to indoor sources, automobile traffic has been recognized as a major source of air pollution exposure. Traffic emissions consist of volatile hydrocarbons, airborne particles, nitrogen oxides, and carbon monoxide. Several recent studies suggest an association between air pollution from traffic and adverse effects on respiratory health (*1-6*). In many of these studies, crude measures of exposure to traffic-related air pollution, such as traffic density on the street of residence and/or distance of the home address to busy roads, are used (*1,2*). Some other studies have used air pollution levels measured at a central ambient site or in the schools of the children (*3-5*). Few studies have incorporated personal measurements of traffic-related air pollution, either as a direct measure of exposure or as a validation of the exposure measures used (*6,7*).

Several studies show that ambient air pollution from traffic is higher in urban areas than in rural or nonurban areas (*8-10*). For example, in the PEACE study, a multicenter study of acute pollution effects on asthmatic children in Europe, the median urban/rural ratio pooled over all 14 locations was 1.8 for nitrogen dioxide (NO_2) and 1.4 for black smoke (*8*). Although none of these studies have related air pollution concentrations to some measure of the actual degree of urbanization, it can be expected that with increasing degree of urbanization, for example, expressed as the number of addresses per unit area, exposure to traffic-related air pollution will increase as well.

Studies have shown also that air pollution from traffic is higher along busy roads compared to background locations (*11-13*). Air pollution from traffic in city districts near highways is related to the traffic density of the highway, distance of the measuring site to the highway, and the percentage of time that the measuring site was downwind of the highway (*14*). The range in concentrations between the city districts located along highways with different traffic densities was larger than the variation with distance from the highway within city districts. It was therefore suggested that exposure to traffic-related air pollution varies less among subjects living within the same city district than among subjects living along highways with different traffic densities.

This study was designed to test two (null) hypotheses: *a*) there is no difference in exposure to NO_2 as a marker of traffic-related air pollution among subjects living in areas with a different degree of urbanization; and *b*) there is no difference in exposure to NO_2 as a marker of traffic-related air pollution among subjects living close to highways with different traffic intensities.

Materials and Methods

We used NO_2 as a marker for traffic-related air pollution (*3,6*). Personal exposure to NO_2 was measured in children from six different schools. Three schools were situated in city districts with varying degrees of urbanization, with no busy streets within 300 m of the schools. The other three schools were within 400 m of highways with varying traffic densities. In addition to personal measurements of the children, parents were asked to perform outdoor NO_2 measurements at the back side of their homes. Weekly averaged measurements were conducted during four different seasons.

Study Locations

For the first part, three schools were chosen located in areas with various degrees of urbanization. The degree of urbanization, developed by the Dutch Central Bureau of Statistics, is based on the average address density per unit area. It classifies all Dutch municipalities in 5 degrees of urbanization, with 1 being the most-populated level and 5 the least-populated level, so that each group has approximately the same number of inhabitants. Three schools from municipalities with a degree of urbanization of 1 (very urban), 3 (fairly urban), and 5 (nonurban) were selected from all schools in the center of the Netherlands (Utrecht province). Schools were selected on the basis of two criteria: *a*) the degree of urbanization of the postal code area of the school was the same as for the whole municipality; and *b*) the schools were more than 300 m from busy roads. The urban densities of the postal code areas of the

selected schools were 3,792; 1,481; and 195 addresses per square kilometer for degree of urbanization of 1, 3, and 5, respectively. The years of construction of the school buildings were 1937, 1985, and 1967 for degree of urbanization of 1, 3, and 5, respectively.

For the second part of the study, 3 schools were chosen from 24 schools participating in a study on health effects of exposure to traffic-related air pollution of children attending schools within 400 m of highways (*15*). In the selection of the schools, goals were a maximum variation in total traffic density and a minimum variation in the geographic locations of the schools with respect to the highways. The latter criterion was used to reduce differences in the percentages of time that the schools would be downwind during the measurements. The selected schools were situated in the southwest of the Netherlands. The schools were classified as very busy (169,637 vehicles/24 hr), fairly busy (126,115 vehicles/24 hr) and not busy (45,129 vehicles/24 hr) according to the total traffic density of the nearby highway. Characteristics of the selected schools are listed in Table 1. The school along the highway with the lowest traffic density was in an area with a lower degree of urbanization and was closer to the highway than the other two schools. The geographic location of this school with respect to the highway also deviated approximately 29° from the geographic location of the two other schools. The school building along the very busy highway was older (year of construction, 1929) than the other two school buildings (years of construction, 1973 and 1979 for the school along the fairly busy and not busy highway, respectively).

Table 1. Characteristics of the three schools situated close to a highway.

							Degree of urbanization	
Category	Highway	Total traffic[a]	Car traffic[b]	Truck traffic[c]	Orientation[d]	Distance from highway (m)	Level	Addresses/km^2
Very busy	A20	169,637	149,450	20,187	168°	349	1	2,950
Fairly busy	A20	126,115	105,810	20,305	169°	335	1	2,689
Not busy	A58	45,129	39,939	5,190	197°	62	3	1,252

[a]Number of vehicles per 24 hr. [b]Number of vehicles < 5.1 m length per 24 hr. [c]Number of vehicles > 5.1 m length per 24 hr. [d]Geographic location with respect to the highway.

Sampling Strategy

Children between 6 and 12 years of age were asked to participate in the study. All children of a class were asked to participate by handing out information letters and informed consent forms for their parents. Two to four classes per school were approached, depending on the number of children per class. A total of 397 children were asked to participate in the study. The study started in the autumn with 222 (56%) children. In the winter 19 additional children volunteered to participate. One new child started in the spring. During the course of the study, 10 children dropped out.

Personal NO_2 exposure of the children and outdoor NO_2 at the back side of their homes were measured during 1 week in four different seasons. Concentrations of indoor NO_2 in the classrooms and outdoor NO_2 at the back side of the schools were measured in the same week. During autumn, winter, and spring, measurements were conducted for all six schools simultaneously. For logistic reasons it was not possible to conduct all measurements in the same week in the summer. In the summer, therefore, the measurements of the urbanization schools and traffic schools were conducted in 2 separate weeks. The school along the highway with the highest traffic density did not participate during the summer season.

Sampling sites of indoor measurements at school were located in the classrooms of the participating children, away from windows and doors. Outdoor measurements at the schools were conducted at the back side of the school at approximately 1.5-2 m above the ground. Children received verbal instructions from one of the investigators at the school on how to take care of their samplers. Passive sampling tubes were attached to a badge and worn between breast and head. Outdoor samplers were given to the children, with written instructions for the parents. With the aid of photographs and examples, these written instructions explained the use of the personal exposure badges of their children and the measurement of outdoor NO_2 at their homes. Personal exposure sampling was initiated and stopped at school. In small groups of five, children were asked to uncap tubes and after 1 week, to recap their tubes under supervision. The supervising researcher registered date and time. Parents were instructed to attach the outdoor tubes to the back side of their homes using a specially designed device and to write down on a form the time of uncapping and recapping. The sampled outdoor tubes were handed in by the children on the same day that the personal exposure samples were collected. Tubes handed in after the collection day were sent back by mail by the teacher, using a preaddressed envelope. Collected tubes were sealed and stored in a refrigerator until analysis (within 3 months). To motivate the children, teachers were encouraged to wear NO_2 samplers as well. After each measurement, children were given a small present. After winter the children were given a presentation on the progress of the study to further motivate them.

Sampling Methods

NO_2 was measured using diffusion tubes described by Palmes et al. (*16*). These tubes consisted of a transparent cylinder closed at one end with a red

cap containing a metal grid coated with triethanolamine. All measurements were conducted in duplicate, and the average was used in the statistical analyses. A total of 902 pairs of personal sampling tubes and 842 pairs of outdoor sampling tubes were handed out. The number of outdoor samples was lower than the number of personal tubes because if more than one child in the same household participated, tubes for outdoor sampling were given only to the oldest child. As a result, 17 children from 16 different households did not receive any outdoor tubes. A total of 839 (93%)-sampled personal duplicates and 750 (89%)-sampled outdoor duplicates were collected and analyzed. Five personal and 28 outdoor concentrations could not be calculated because of missing information in the sampling times. Another 7 outdoor concentrations were excluded because the measurement time was less than 4 days. In addition, 43 personal duplicates and 7 outdoor duplicates were excluded because of bad reproducibility (coefficient of variation [CV] > 25%). The mean CV of the remaining duplicates was 6.7% (SD 5.8; median 5.2%) for personal measurements and 6.3% (SD 5.5; median 4.7%) for outdoor measurements. In total, 791 (88% of distributed) personal and 708 (84% of distributed) outdoor concentrations were obtained. These also include measurements of children who participated in fewer than four seasons.

Exposure Variables

Information on potential indoor sources of NO_2 in the homes of the children and other characteristics was assessed using a self-administered questionnaire distributed at the beginning of the project.

For children from the three schools near a highway, the distance of the home from the highway, defined as the distance between the center of the postal code area of the home address to the highway, was calculated using a geographic information system (GIS). In addition, wind direction was used to evaluate the percentage of time the schools were downwind of the highway during the measurement periods. Data on wind direction per hour were obtained from Rotterdam Airport Zestienhoven of the Royal Dutch Meteorological Institute. The percentage of time that a school had been downwind of the highway was calculated by determining a 120° sector surrounding the perpendicular line connecting the school to the highway (*14*).

Data Analysis

First, the distribution of personal and outdoor NO_2 concentrations was calculated for each school and season separately. Differences among the schools were tested using a *t*-test. Because of the known strong influence of unvented gas water heaters on indoor NO_2 concentrations in the Netherlands (*17,18*), children whose parents reported that they had such a water heater were excluded from the analysis.

Combined analysis of data from all four seasons was performed using a multiple regression model in which three dummy variables for each season were included. The SAS procedure "Proc Mixed" (SAS Institute, Cary, North Carolina, USA) was used to adjust regression results for correlations between repeated measurements of the same child. A random intercept model was used. The all-seasons combined effect of degree of urbanization or traffic density on personal and outdoor NO_2 was calculated using both the categoric urbanization/traffic density levels (very, fairly, non) as the continuous urbanization/traffic density variables (addresses per square kilometer and vehicles per 24 hr for urbanization and traffic density, respectively).

For both groups of three schools, combined season analyses for personal exposure were also calculated after adjusting for the following potential indoor sources of NO_2: unvented gas water heater, vented gas water heater, gas cooker, parental smoking, and a gas space heater in the living room. For the traffic density schools the distance between the home address and the highway was added to the model. We expected an exponential decay of the concentrations with increasing distance from the road (*14*), so we used the logarithm of the distance. Furthermore, we evaluated any significant differences in the personal/outdoor ratios between the schools that, if present, could point to differences in personal exposures between the schools caused by factors other than the outdoor NO_2 concentrations or the indoor sources mentioned previously.

Results

Population

Characteristics of the participating children are shown in Table 2. The number of participants was smallest for the schools in the area with the highest degree of urbanization and along the busiest highway. Potential indoor sources were generally present more in the homes of the children from the highest exposure category, especially for the urbanization schools. In total, 14 children lived in a home with an unvented gas water heater ("geiser"). In most households, gas was used for cooking.

Table 2. Characteristics of the participating children.

	Urbanization schools			Traffic schools		
Characteristic	Very urban (*n* = 33) 3,792 addresses/km² *n* (%)	Fairly urban (*n* = 56) 1,481 addresses/km² *n* (%)	Nonurban (*n* = 43) 195 addresses/km² *n* (%)	Very busy (*n* = 27) 169,637 vehicles/24 hr *n* (%)	Fairly busy (*n* = 39) 126,115 vehicles/24 hr *n* (%)	Nonbusy (*n* = 44) 45,129 vehicles/24 hr *n* (%)
Girls	19 (58)	32 (57)	24 (56)	12 (48)	20 (51)	22 (50)

Unvented gas water heater	5 (15)	0 (0)	0 (0)	5 (20)	2 (5)	2 (5)
Vented gas water heater	8 (24)	1 (2)	2 (5)	3 (12)	0 (0)	6 (14)
Cooking with gas	33 (100)	48 (86)	29 (67)	24 (100)	31 (82)	34 (79)
Parental smoking	22 (82)	24 (43)	22 (51)	17 (68)	14 (36)	28 (64)
Gas space heater in living room	3 (9)	5 (9)	15 (35)	2 (8)	3 (8)	8 (18)
Dutch origin	10 (33)	52 (93)	43 (100)	21 (84)	33 (85)	36 (82)
Low-education[a] mother	15 (58)	3 (6)	2 (5)	8 (36)	2 (5)	8 (18)
Low-education[a] father	16 (57)	3 (6)	5 (13)	2 (10)	1 (3)	6 (14)
Home within 400 m of the highway				16 (64)	20 (51)	32 (74)
Home within 1,000 m of the highway				21 (84)	32 (82)	43 (100)

[a]Primary school only.

NO_2 Concentrations and Degree of Urbanization

Results of the classroom and outdoor NO_2 measurements at the schools in areas with varying degrees of urbanization are presented in Table 3. Except for the classroom concentrations in autumn, classroom concentrations and outdoor concentrations at the back side of the schools were in all seasons highest in the area with the highest degree of urbanization and lowest in the area with the lowest degree of urbanization. The difference among average classroom concentrations in the very urban and nonurban school (12.2 $\mu g/m^3$) was somewhat larger than the difference among the average outdoor concentrations (11.4 $\mu g/m^3$). This indicates that the indoor/outdoor ratio (I/O) was larger for the very urban school (yearly average I/O = 0.6) compared to the other two urbanization schools (yearly average I/O = 0.4). As there are no important indoor sources of NO_2 in these classrooms, this is possibly the result of higher ventilation of the very urban school in the very urban area. This is supported by the fact that this school building was much older (pre-World War II) than the other two school buildings.

Table 3. Mean classroom and outdoor school NO_2 concentrations at schools in areas with varying degrees of urbanization.

	Classroom mean[a]			Outdoors school		
Period (dd/mm/yy)	**Very urban 3,792 addresses/km^2**	**Fairly urban 1,481 addresses/km^2**	**Nonurban 195 addresses/km^2**	**Very urban 3,792 addresses/km^2**	**Fairly urban 1,481 addresses/24 km^2**	**Nonurban 195 addresses/km^2**
Autumn (24/11/97-01/12/97)	20.9	8.0	9.3	31.6	27.6	26.7
Winter (10/02/98-17/02/98)	29.4	16.0	12.4	59.0	41.6	33.2
Spring (17/04/98-24/04/98)	22.9	13.4	12.5	32.4	29.2	26.8
Summer (19/06/98-	19.0	12.4	9.6	24.8	20.5	15.7

26/06/98)						
Average	23.1	12.5	10.9	37.0	29.7	25.6

[a]Mean of 2-4 classrooms.

The distributions of personal and home outdoor NO_2 concentrations in areas with varying degrees of urbanization are presented in Table 4. In all seasons, both personal and outdoor NO_2 concentrations were highest in the area with the highest degree of urbanization and lowest in the area with the lowest degree of urbanization. The difference between outdoor concentrations in the very urban and nonurban areas was significant in all seasons except autumn, which may be due to the low number of outdoor concentrations in the very urban area (n = 9). When comparing the very urban with the fairly urban area, we found significant differences ($p < 0.05$) in autumn, winter, and spring for personal exposures, and in winter, spring, and summer for outdoor concentrations.

Table 4. Distribution of personal and home outdoor NO2 concentrations of children attending schools in areas with varying degrees of urbanization.

	Personal NO_2 concentrations									Home outdoor NO_2 concentrations								
	Very urban 3,792 addresses/km^2			Fairly urban 1,481 addresses/km^2			Nonurban 195 addresses/km^2			Very urban 3,792 addresses/km^2			Fairly urban 1,481 addresses/km^2			Nonurban 195 addresses/km^2		
	n	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range
Autumn	14	25.9**	15.3-43.8	47	18.7**	8.6-58.9	41	14.2	7.7-23.8	9	29.8	16.5-36.4	48	27.0**	9.0-34.9	38	24.7	16.9-31.3
Winter	26	42.1**	21.3-163.1	47	23.4**	10.1-45.3	35	19.1	12.5-30.8	20	49.0	30.1-71.4	46	41.5**	25.2-49.5	40	36.1	21.7-43.5
Spring	19	33.3**	13.9-110.4	53	19.6**	4.7-30.1	39	15.8	9.1-23.6	10	38.1**	30.2-70.1	47	29.8**	18.6-36.6	35	22.6	6.1-29.7
Summer	22	19.7**	9.2-30.9	52	17.8**	10.2-29.6	42	14.8	7.2-29.6	14	25.6**	12.9-40.1	51	21.3**	8.3-26.6	37	16.0	7.3-20.8

**Significantly different from the school in the nonurban area; $p < 0.01$.

When the data from all seasons were combined, the estimated difference between the area with the highest degree of urbanization and the area with the lowest degree of urbanization was 14.6 μg/m^3 (standard error of the mean [SE] 1.7) for personal exposures and 11.0 μg/m^3 (SE 0.9) for outdoor concentrations. The estimated differences between the area with the intermediate degree of urbanization and the area with the lowest degree of urbanization were 3.9 μg/m^3 (SE 1.3) for personal exposures and 5.0 μg/m^3 (SE 0.6) for outdoor concentrations. Table 4 shows that for the school in the very urban area the range in personal NO_2 concentration was large in both winter and summer, which in both seasons is caused by an outlying high concentration from the same child (who lived in a home with a vented gas water heater). Removing these outliers somewhat decreased the estimated difference in personal exposures between the very urban and nonurban area (from 14.6 to 12.3 μg/m^3). When the degree of urbanization of the home address in addresses per square kilometer instead of the categoric urbanization level of the school was included in the model, an increase in NO_2 concentrations of 3.4 μg/m^3 per 1,000 addresses per km^2 was estimated for both personal and outdoor concentrations (SE 0.4 and 0.3, respectively).

NO_2 Concentrations and Traffic Density

Table 5 shows the percentages downwind, classroom concentrations, and outdoor concentrations during the measurement periods. On average, the percentage of time that the school was downwind of the highway during the measurements was 15% higher for the school with the lowest traffic density compared to the other two schools. Outdoor NO_2 concentrations at the back side of the schools were, on average, highest for the school along the very

busy highway and lowest for the school along the nonbusy highway. Mean classroom concentrations were for all seasons highest in the school along the very busy highway but did not differ much between the two other schools.

Table 5. Mean classroom and outdoor school NO_2 concentrations at schools near highways with varying traffic intensities.

Period (dd/mm/yy)	Percentage of time downwind			Classroom mean[a]			Outdoors school		
	Very busy 169,637 v/24 hr	Fairly busy 126,115 v/24 hr	Nonbusy 45,129 v/24 hr	Very busy 169,637 v/24 hr	Fairly busy 126,115 v/24 hr	Nonbusy 45,129 v/24 hr	Very busy 169,637 v/24 hr	Fairly busy 126,115 v/24 hr	Nonbusy 45,129 v/24 hr
Autumn (25/11/97-02/12/97)	66	66	46	19.1	11.9	8.5	-[b]	-[b]	35.1
Winter (09/02/98-16/02/98)	34	34	89	33.5	16.0	19.3	82.3	57.0	46.7
Spring (16/04/98-23/04/98)	53	53	49	25.3	17.1	16.9	36.8	37.1	32.3
Summer (07/07/98-14/07/98)	39	39	67	19.2	12.5	13.0	21.8	17.3	19.5
Average	48	48	63	24.3	14.4	14.4	47.0	37.1	33.4

v, vehicles.
[a]Average of two classrooms. [b]Missing because of vandalism or measurement failure.

The distributions of the personal and home outdoor NO_2 concentrations for children living near highways are presented in Table 6. In all seasons, personal and outdoor NO_2 concentrations were significantly higher for the very busy highway compared to the nonbusy highway. NO_2 concentrations along the fairly busy highway were significantly higher compared to the nonbusy highway in the winter and spring season. For outdoor NO_2 this was also the case in the summer season. Significant differences in personal and outdoor NO_2 concentrations between the very busy and fairly busy highway were found only in the autumn period.

Table 6. Distribution of personal and home outdoor NO2 concentrations of children attending schools near highways with varying traffic intensities.

	Personal NO_2 concentrations									Home outdoor NO_2 concentrations								
	Very busy 169,637 v/24 hr			Fairly busy 126,115 v/24 hr			Nonbusy 45,129 v/24 hr			Very busy 169,637 v/24 hr			Fairly busy 126,115 v/24 hr			Nonbusy 45,129 v/24 hr		
	n	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*	Mean	Range
Autumn	9	26.1*	16.5-37.0	36	19.2	6.4-28.1	41	19.1	9.3-45.7	12	38.0*	26.7-52.9	37	31.9	24.0-37.0	31	34.0	24.2-44.7

Winter	14	36.0*	18.0-82.6	32	29.7*	16.6-46.8	36	25.1	14.1-59.9	20	58.3**	48.5-67.2	35	56.1**	43.1-82.1	33	44.9	36.0-66.9
Spring	15	29.2**	6.0-54.0	32	25.0**	11.9-41.6	37	18.2	6.4-27.3	16	39.3**	10.3-54.7	34	34.9**	26.0-44.8	31	26.9	13.5-35.3
Summer	30	15.6	7.2-25.3	33	15.1	8.9-21.5	31	17.9**	13.7-22.1	33	15.7	9.6-20.1						

*Significantly different from the school along the nonbusy highway; $p < 0.05$. **Significantly different from the school along the nonbusy highway; $p < 0.01$

Combining the seasons for 1 year resulted in an estimated difference of 8.2 μg/m^3 (SE 1.8) between personal NO_2 exposure of the children from the school with the highest traffic density and the school with the lowest traffic density. Personal NO_2 exposure of the children from the school with the intermediate traffic density was 2.6 μg/m^3 (SE 1.4) higher compared to the school with the lowest traffic density. For outdoor NO_2 concentrations these differences were 9.6 μg/m^3 (SE 1.1) and 4.9 (SE 0.8), respectively. When total traffic density of the highway as a continuous variable was included in the model, an increase in NO_2 concentrations of 2.6 μg/m^3 (SE 0.6) per 50,000 vehicles per 24 hr was estimated for personal exposure and 3.5 μg/m^3 (SE 0.4) per 50,000 vehicles per 24 hr for outdoor concentrations. Adding the logarithm of the distance of the home address to the highway to the model did not strongly influence the estimates for traffic density (both categoric and continuous). Outdoor concentrations significantly decreased with increasing distance. The estimated decrease was -1.3 μg/m^3 per log(m) (SE 0.4). This corresponds to a difference of 1.8 μg/m^3 when comparing the concentration at 100-m distance to the concentration at 400-m distance. For personal NO_2 concentrations the influence of distance of the home address was smaller (-0.9 μg/m^3 per log(m); SE 0.8) and not significant.

Indoor Sources

As expected, having an unvented gas water heater in the home strongly influenced personal NO_2 exposures, with an estimated contribution of 27.0 μg/m^3 (SE 4.4) for the urbanization schools and 19.8 μg/m^3 (SE 2.7) for the traffic schools. A vented gas water heater had a smaller but also significant influence on personal NO_2 exposures of 5.4 μg/m^3 (SE 3.1) and 8.9 μg/m^3 (SE 2.5) for the urbanization and traffic schools, respectively. Cooking with gas also significantly contributed to personal NO_2 exposures, with an estimated contribution of 2.4 μg/m^3 (SE 0.9) for the urbanization schools and 2.3 μg/m^3 (SE 1.3) for the traffic schools. Parental smoking or having a gas space heater in the living room did not significantly influence personal NO_2 exposures.

Differences in personal NO_2 exposures between the urbanization and traffic categories remained significant after adjusting for potential indoor sources. For the urbanization schools, the estimated difference between the very urban and nonurban school, after excluding data from children with either an unvented or vented gas water heater and after adjusting for cooking with gas, parental smoking, and a gas space heater in the living room, was 10.1 μg/m^3 (SE 1.2). This is lower than the uncorrected value of 14.6 μg/m^3, suggesting that the unadjusted difference was partly caused by indoor sources. The adjusted difference between the fairly urban and nonurban school was 3.3 μg/m^3 (SE 0.8), which is similar to the unadjusted value of 3.9 μg/m^3. For the traffic schools, the difference between the very busy and nonbusy highway did not change (8.2 μg/m^3; SE 1.6) and the difference between the fairly busy and nonbusy highway increased from 2.6 μg/m^3 to 4.5 μg/m^3 (SE 1.1). Furthermore, the adjusted model showed a significant decrease in personal NO_2 exposure with increasing distance of the home address from the highway of -1.4 μg/m^3 per log(m) (SE 0.6), whereas in the uncorrected analysis this decrease was smaller and not significant. Including some socioeconomic factors, such as Dutch origin, parental education, or the age of the home, did not change the results.

When all data included in Table 4 were used, the average personal/outdoor ratio was about 0.2 ($p < 0.01$) higher for the very urban school compared to the other two urbanization schools, again pointing toward a stronger influence of indoor sources on personal NO_2 exposures of children from the very urban school. After excluding data from children with (un)vented gas water heaters in their homes, and after adjusting for cooking with gas, parental smoking, and the presence of a gas space heater in the living room, the difference was less than 0.1 and no longer statistically significant. No significant differences between the personal/outdoor ratios between the traffic schools were found in any of the analyses.

Comparison between Urbanization and Traffic Density Schools

Because measurements were conducted in all six schools simultaneously in autumn, winter, and spring, a direct comparison between schools from the two different parts of the study is possible for these three seasons. Outdoor concentrations at the back side of the schools (Tables 3, 5) were generally higher for the schools along highways compared to the other school with the same degree of urbanization (very busy and fairly busy compared to very urban and not busy compared to fairly urban). Classroom concentrations were, on average, higher in the school along the busiest highway compared to the very urban school and in the school along the least busy highway compared to the fairly urban school. Classroom concentrations, however, were considerably lower in the fairly busy compared to the very urban school. Home outdoor concentrations were significantly higher along highways. The combined season estimated differences were 6.7 μg/m^3 and 3.0 μg/m^3 for the very busy and fairly busy highway compared to the very urban school, and 2.5 μg/m^3 for the nonbusy highway compared to the fairly urban school. Personal exposures, however, were not higher along highways. Personal exposures were actually significantly lower along the fairly busy highway than in the very urban area (estimated difference 5 μg/m^3; SE 2).

Discussion

This study has shown that personal and outdoor NO_2 concentrations were significantly different among children living in areas with different degrees of urbanization and among children living in areas close to highways with different traffic densities.

Several other studies have documented significantly higher NO_2 concentrations in urban areas compared to nonurban, suburban, or rural areas (*19-22*). The estimated differences between the very urban and nonurban area of 10 and 11 µg/m³ for personal and outdoor concentrations, respectively, correlate well with the differences found in other European studies with similar NO_2 levels (*19-21*). In a study in Helsinki, Finland, personal NO_2 exposures of 246 children 3-6 years of age from eight day-care centers in downtown and suburban areas measured during 13 weeks were about 9 µg/m³ higher in the downtown area (geometric mean, 26.5 µg/m³) than in the suburban area (geometric mean, 17.5 µg/m³) (*19*). Krämer et al. (*6*) measured outdoor and personal NO_2 exposures as part of a study on the health effects of traffic pollution on children living in two urban and one suburban area. Estimated annual personal and outdoor NO_2 concentrations were 5-7 µg/m³ and 12-17 µg/m³ higher, respectively, in the urban areas compared to the suburban area.

Less information is available about NO_2 concentrations in city districts along highways with varying traffic densities. The 3 schools that participated in this study were selected out of 24 schools that participated in a study on health effects of exposure to traffic-related air pollution of children attending schools near highways (*15*). In that study, indoor and outdoor NO_2 concentrations measured at the schools were significantly correlated with total traffic density of the highway. The estimated contribution of total traffic was 3 µg/m³ per 50,000 vehicles for both outdoor and indoor air, which is similar to the values found in this study (2.6 and 3.5 µg/m³ per 50,000 vehicles for personal and home outdoor concentrations, respectively). In a previous study on air pollution near highways in the Netherlands, we also found a significant correlation ($r = 0.68$) between total traffic density and indoor NO_2 concentrations in 12 schools (*14*). In that study, mean classroom NO_2 concentrations varied between 9.2 µg/m³ at 393 m of a highway with a total traffic density of 81,000 vehicles per 24 hr to 32.8 µg/m³ at 33 m from a highway with 133,000 vehicles per 24 hr. Krämer et al. (*6*) found a correlation ($r = 0.70$) between outdoor NO_2 and an index characterizing the amount of traffic in front of the child's home. Personal NO_2 exposures were only marginally correlated with outdoor NO_2 ($r = 0.37$).

Personal and home outdoor NO_2 concentrations significantly decreased with increasing distance of the home address to the highway. The estimated decrease was 1.3 and 1.4 µg/m³ per log(m) for home outdoor and personal NO_2, respectively, corresponding to a decrease of about 2 µg/m³ when expressed as the difference between 100 and 400 m distance. Compared to the difference observed between the very busy freeway and the quiet freeway, which was more than 10 µg/m³, this difference was modest, indicating that traffic density on a freeway is a more important determinant of personal NO_2 exposure than distance of home or school from the freeway. For all 24 schools a somewhat higher but nonsignificant value of 1.9 µg/m³ per log(m) was found for both outdoor and classroom concentrations (*15*). In our previous study on air pollution near highways, we also found a significant correlation between indoor NO_2 concentrations in classrooms and distance of the school to the highway ($r = -0.83$). Furthermore, outdoor NO_2 measurements at various distances from the same highway showed a clear gradient (*14*). Two other studies in open terrain downwind of a highway also found a decline in NO_2 concentrations with distance (*23,24*). Nakai et al. (*7*) measured personal, indoor, and outdoor NO_2 concentrations in three zones at different distances from two busy roads in Tokyo, Japan. Mean outdoor concentrations decreased from 81 µg/m³ in zone A (< 20 m) to 67 µg/m³ in zone B (20-150 m) and 39 µg/m³ in the reference zone (zone C). Average personal NO_2 exposures in the nonheating season were 60, 56, and 32 µg/m³ for zone A, B, and C, respectively. Two other Japanese studies also documented associations between NO_2 concentrations and distance to major roads (*20,25*).

Differences between the schools remained significant after excluding children with either vented or unvented gas water heaters in their homes (the two known strongest indoor sources of NO_2 in the Netherlands) and after adjusting for cooking with gas, parental smoking, and a gas space heater in the living room. Including some socioeconomic variables or housing characteristics also did not change the results. In view of our specific research hypothesis, other unidentified indoor sources can only invalidate our conclusions in case the presence of these factors is associated with the degree of urbanization or traffic density. Randomly distributed indoor sources could only have obscured the observed relationship between personal NO_2 and traffic. It is unlikely that any unidentified indoor source is sufficiently strong and sufficiently overrepresented in the highest exposure category to explain the observed differences between the schools. The same holds for other factors that may influence personal NO_2 exposures, such as activity patterns. Furthermore, after adjusting for indoor sources, personal/outdoor ratios did not significantly differ between the schools, which further supports the conclusion that the differences in personal exposures between the schools are most likely caused by differences in outdoor concentrations and not by indoor sources or housing characteristics.

The schools along the very and fairly busy highway were situated in a very urban area, whereas the school along the nonbusy highway was situated in an area with a lower degree of urbanization. As a result, differences between the schools could also have been caused by a difference in urbanization. When comparing the highway schools with the urban schools, home outdoor concentrations were significantly higher for the schools along highways than for the urbanization school from the area with the same degree of urbanization. No such differences, however, were found for personal NO_2 exposures. Personal NO_2 exposures of children from schools along the fairly busy highway were even significantly lower than for personal exposures of children from the very urban school. Outdoor NO_2 concentrations measured at the back side of these schools were similar. Classroom concentrations, however, were much lower in the school along the fairly busy highway than in the school in the very urban area, especially in the autumn and winter, suggesting a difference in the ventilation of the schools. Nevertheless, personal NO_2 exposures were significantly higher along the very busy highway than those along the fairly busy highway. This difference was also present after taking into account potential indoor sources. As these two schools were in city districts with similar degrees of urbanization, at similar distances from the road, and with the same geographic orientation toward the road, these differences are most likely caused by the difference in traffic densities of the highways. The difference between these two schools and the school along the highway with the lowest traffic density could (partly) have been caused by a difference in urbanization. Conversely, the latter school was situated closer to the road and was about 15% more downwind of the highway than the first two schools during the measurements. This could have resulted in a smaller difference between the fairly busy and nonbusy highway than would have been observed if all schools had been situated at the same distances from the road and had been downwind for a similar percentage of time.

Personal NO_2 exposures were significantly higher for children who lived in homes with a gas-fired water heater, especially when the water heater had no ventilation duct. This is in line with previous Dutch NO_2 monitoring studies, which have shown that these kinds of water heaters are a major source of indoor NO_2 in the Netherlands (*17,18*). For example, Fischer et al. (*18*) found an estimated difference in personal NO_2 between women living in homes with and without a gas water heater of 24 µg/m³ in the case of an unvented water heater and 12 µg/m³ in the case of a vented gas water heater. Cooking

with gas also significantly increased personal NO_2 concentrations, but this influence was small (± 2 μg/m^3) compared to the influence of an unvented gas water heater. This is in line with several other studies that have documented significant higher personal NO_2 concentrations for children (*19,26*) or adults (*22*) living in homes where gas is used for cooking. Parental smoking did not significantly influence personal NO_2 exposures. Most of the studies mentioned previously have found higher personal or indoor NO_2 concentrations for smokers or children exposed to environmental tobacco smoke (*19-22,26*). The estimated differences, however, are generally small and not always present in all subgroups. For example, in the study among preschool children in Helsinki, personal NO_2 exposures were, on average, about 4 μg/m^3 higher for children living with smokers in the suburban area (electric cooking only). In the urban area, however, personal NO_2 exposures were higher (± 3 μg/m^3) only for children living with smokers in homes where gas was used for cooking, whereas no difference was found for children living in homes with electric cooking (*19*).

Conclusion

This study has shown that personal and outdoor NO_2 concentrations are significantly influenced by the degree of urbanization of the city district and by the traffic density of and distance to a nearby highway. As NO_2 can be considered a marker for air pollution from traffic, *a*) degree of urbanization, *b*) traffic density, and *c*) distance to a nearby highway can all be used to estimate exposure to traffic-related air pollution.

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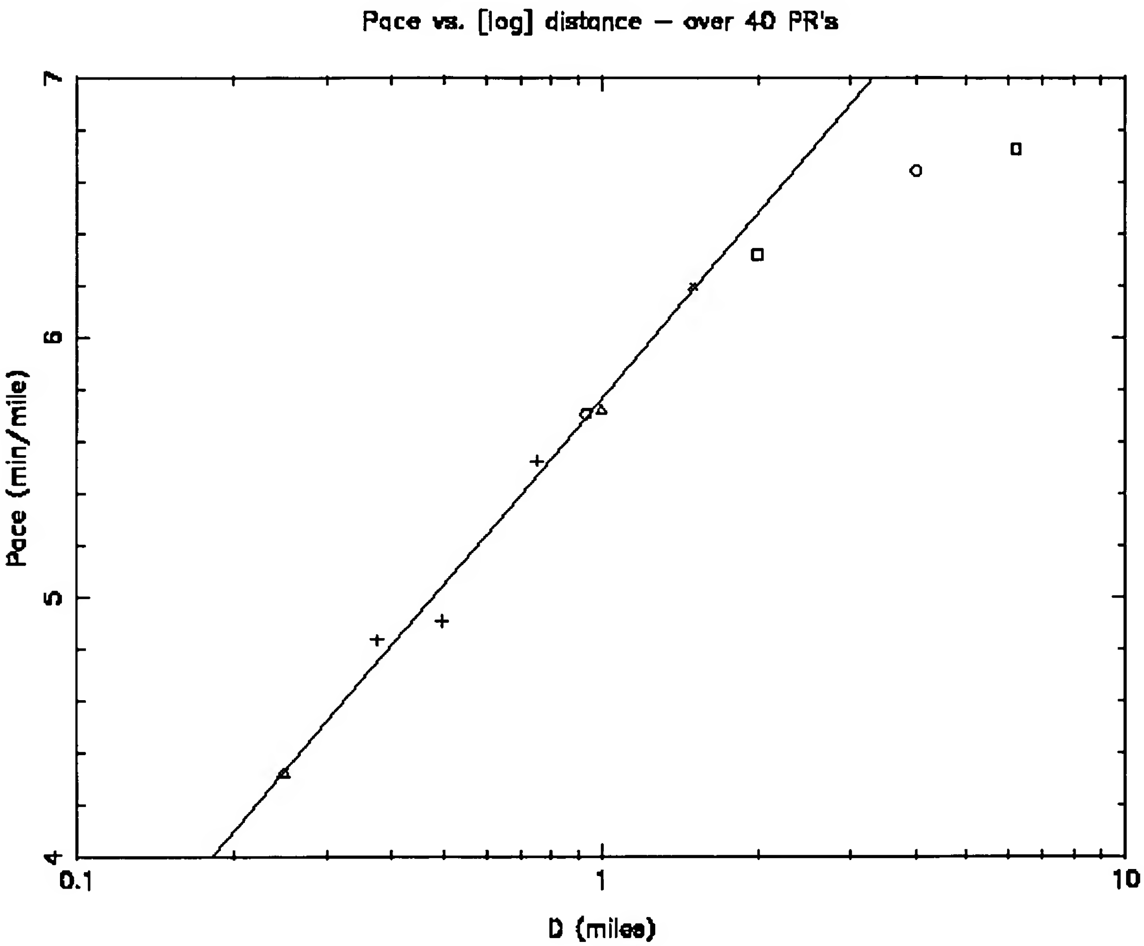
Last Updated: June 8, 2001

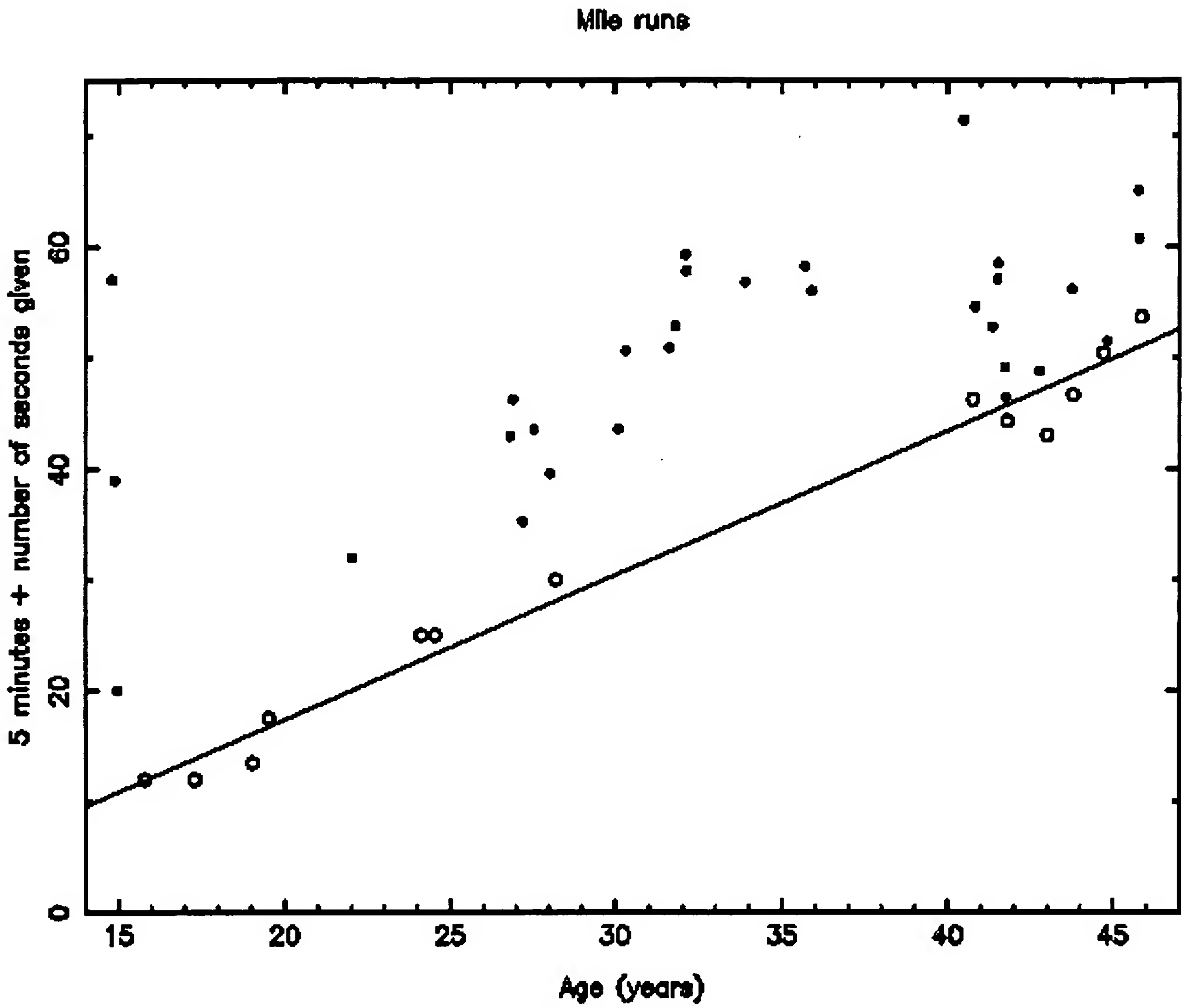
Are you a runner? Do you ever wonder how to determine your potential for running a particular distance at a particular pace? Like many things in physics and physiology, linear relationships can be obtained by taking the logarithms of various quantities and making some plots. The response of the eyeball, for example, is logarithmic. That is why the astronomical magnitude scale is a logarithm of luminosity (to the base 2.511886 = the fifth root of 100). Audio response is also logarithmic, which is why sound engineers work in decibels.

Contemplate the graph below, which is a graph of my best runs since I turned 40, graphed as the pace in minutes per mile vs. the logarithm of the distance in miles. It gives a rather straight line from a quarter mile to 1.5 miles, but then all of a sudden there is a change of slope. In a way I can run 2 miles to 10 km at a pace faster that I'd predict from the shorter runs.



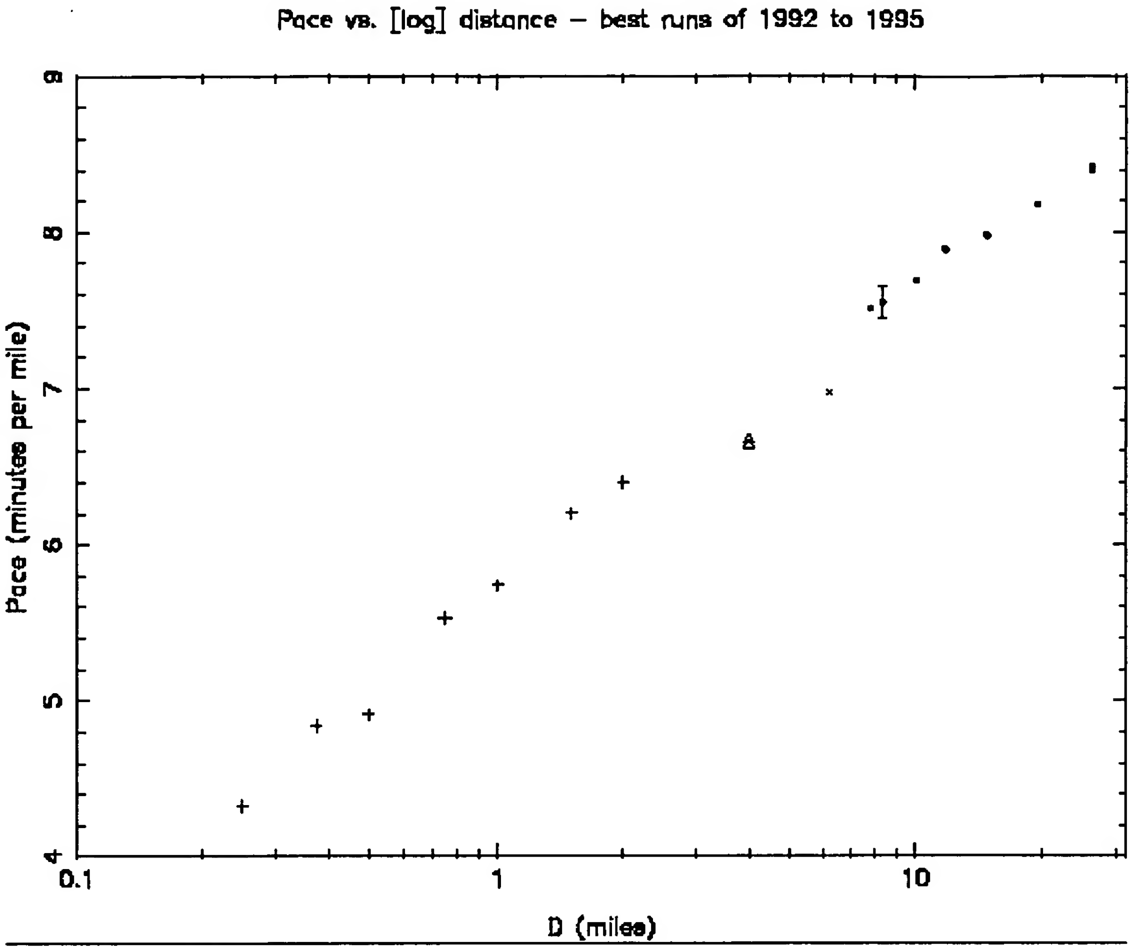
A very similar graph could be obtained for world records, plotting the pace in minutes per kilometer vs. the logarithm of the distance in kilometers.

Here's how my ability to run one mile has changed over the years, starting at age 14.7. If I fit a straight line to the open circles (basically the fastest mile each year) I am getting slower at an average of 1.3 sec per year over 30 years.

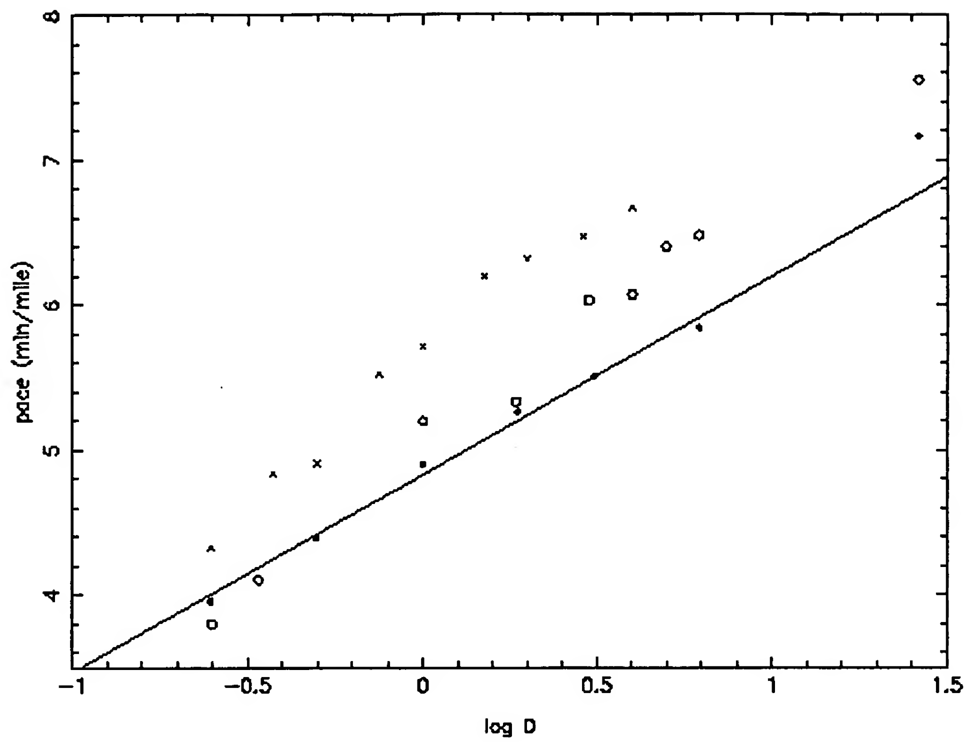


If your pace vs. log D graph has a very shallow slope, then the longer the race is, the more competitive you are. My slope is rather steep, so the shorter races are better for me. The best race distance for me is somewhere between 600 and 800 meters.

I find that this graph can be extended all the way to the marathon distance (see below), but that I have a change of slope right after 2 miles (it becomes shallower), and I have a discontinuity between 6 and 7 miles. At that point I'm just into survival pacing, trying to get to the end without hitting the wall.



In June 1997 Thomas Ehrensperger put together a very interesting web page based on personal records of 84 runners. To view his page click here . Below we show the average PR's of 84 runners (filled dots), my own PR's (open circles), and my best times from 1995 to 1997 (age 41-43; shown as X's). I have fit a straight line to the dots for 400 m through 10 km races. That gives a slope of 1.37, whereas the characteristic slope for my body (from a quarter mile to 1.5 miles seems to be about 2.37.



Go back to Kevin Krisciunas home page by clicking here .

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This document last modified on 17 Aug 1999.

What is Richter Magnitude?

Short answer:

Seismologists use a **Magnitude** scale to express the seismic energy released by each earthquake. Here are the typical effects of earthquakes in various magnitude ranges:

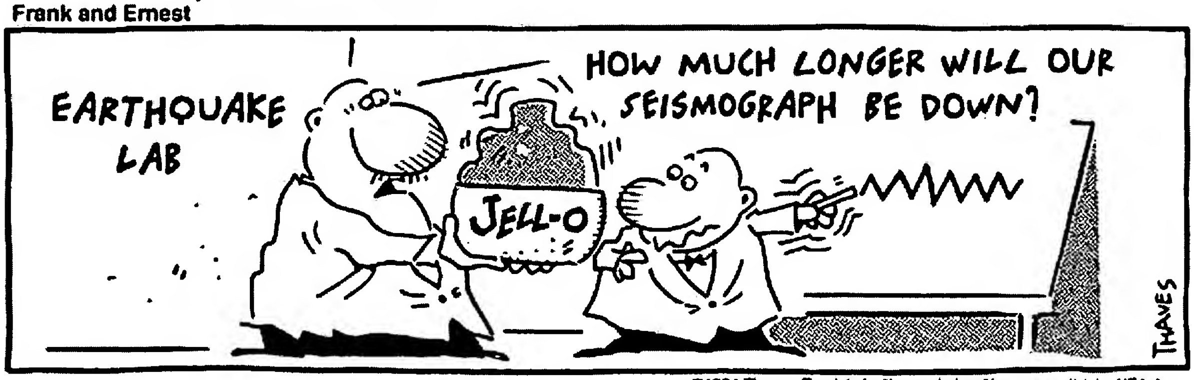
Earthquake Severity

Richter Magnitudes	Earthquake Effects
Less than 3.5	Generally not felt, but recorded.
3.5-5.4	Often felt, but rarely causes damage.
Under 6.0	At most slight damage to well-designed buildings. Can cause major damage to poorly constructed buildings over small regions.
6.1-6.9	Can be destructive in areas up to about 100 kilometers across where people live.
7.0-7.9	Major earthquake. Can cause serious damage over larger areas.
8 or greater	Great earthquake. Can cause serious damage in areas several hundred kilometers across.

Although each earthquake has a unique **Magnitude**, its effects will vary greatly according to distance, ground conditions, construction standards, and other factors. Seismologists use a different Mercalli **Intensity** Scale to express the variable effects of an earthquake.

Each earthquake has a unique amount of energy, but magnitude values given by different seismological observatories for an event may vary. Depending on the size, nature, and location of an earthquake, seismologists use several different methods to estimate magnitude. The uncertainty in an estimate of the magnitude is about plus or minus 0.3 units, and seismologists often revise magnitude estimates as they obtain and analyze additional data.

Frank and Ernest



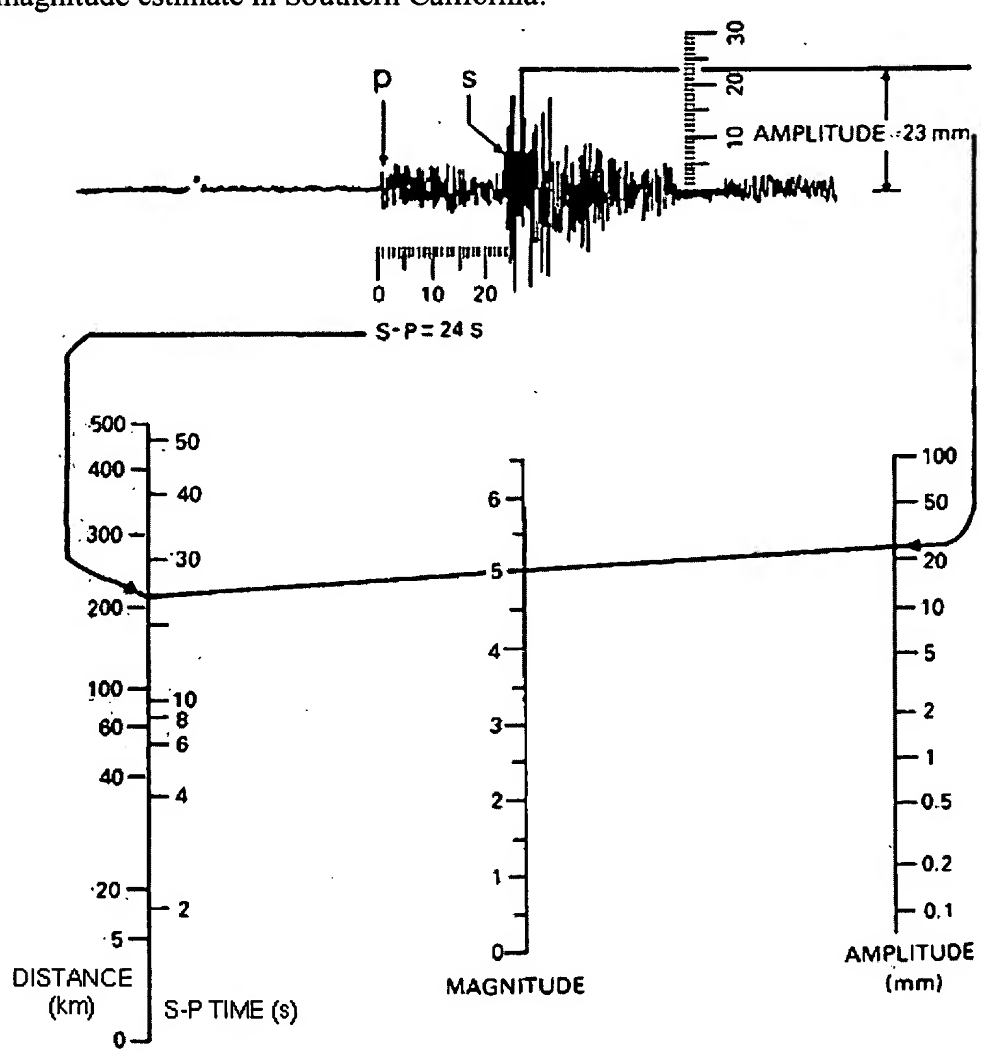
With permission from http://www.comics.com/comics/franknernest/index.html

Long answer:

One of **Dr. Charles F. Richter**'s most valuable contributions was to recognize that the **seismic waves** radiated by all earthquakes can provide good estimates of their magnitudes. You can read about seismic waves by clicking here. He collected the recordings of seismic waves from a large number of earthquakes, and developed a calibrated system of measuring them for magnitude.

Richter showed that, the larger the intrinsic energy of the earthquake, the larger the **amplitude** of ground motion at a given distance. He calibrated his scale of magnitudes using measured maximum amplitudes of shear waves on seismometers particularly sensitive to shear waves with periods of about one second. The records had to be obtained from a specific kind of instrument, called a **Wood-Anderson seismograph**. Although his work was originally calibrated only for these specific seismometers, and only for earthquakes in southern California, seismologists have developed scale factors to extend Richter's magnitude scale to many other types of measurements on all types of seismometers, all over the world. In fact, magnitude estimates have been made for thousands of Moon-quakes and for two quakes on Mars.

The diagram below demonstrates how to use Richter's original method to measure a seismogram for a magnitude estimate in Southern California:



The scales in the diagram above form a **nomogram** that allows you to do the mathematical computation

quickly by eye. The equation for Richter Magnitude is:

$$M_L = \log_{10} A(mm) + (\text{Distance correction factor})$$

Here *A* is the amplitude, in millimeters, measured directly from the photographic paper record of the **Wood-Anderson** seismometer, a special type of instrument. The *distance factor* comes from a table that can be found in Richter's (1958) book Elementary Seismology. The equation behind this nomogram, used by Richter in Southern California, is:

$$M = \log_{10} A(mm) + 3\log_{10}[8\Delta t(s)] - 2.92$$

Thus after you measure the wave amplitude you have to take its **logarithm**, and scale it according to the distance of the seismometer from the earthquake, estimated by the S-P time difference. The S-P time, in seconds, makes Δt.

Click here to learn more about the mathematical logarithm.

Seismologists will try to get a separate magnitude estimate from every seismograph station that records the earthquake, and then average them. This accounts for the usual spread of around 0.2 magnitude units that you see reported from different seismological labs right after an earthquake. Each lab is averaging in different stations that they have access to. It may be several days before different organizations will come to a consensus on what was the best magnitude estimate.

Seismic Moment:

Seismologists have more recently developed a standard magnitude scale that is completely independent of the type of instrument. It is called the **moment magnitude**, and it comes from the **seismic moment**.

To get an idea of the seismic moment, we go back to the elementary physics concept of torque. A torque is a force that changes the angular momentum of a system. It is defined as the force times the distance from the center of rotation. Earthquakes are caused by internal torques, from the interactions of different blocks of the earth on opposite sides of faults. After some rather complicated mathematics, it can be shown that the moment of an earthquake is simply expressed by:

$$(\text{Moment}) = (\text{Rock Rigidity}) \times (\text{Fault Area}) \times (\text{Slip Distance})$$

$$M_0 = \mu A d$$

$$(\text{dyne-cm}) = \left[\frac{\text{dyne}}{\cancel{\text{cm}^2}}\right] \times (\cancel{\text{cm}^2}) \times (\text{cm})$$

The formula above, for the **moment** of an earthquake, is fundamental to seismologists' understanding of how dangerous faults of a certain size can be.

Now, let's imagine a chunk of rock on a lab bench, the rigidity, or resistance to shearing, of the rock is a **pressure** in the neighborhood of a few hundred billion dynes per square centimeter. (Scientific notation makes this easier to write.) The **pressure** acts over an **area** to produce a force, and you can see that the cm-squared units cancel. Now if we guess that the distance the two parts grind together before they fly apart is about a centimeter, then we can calculate the moment, in dyne-cm:

$$M_0 = (3\times10^{11}\ \frac{dyne}{\cancel{cm^2}})(10\ \cancel{cm})(10\ \cancel{cm})(1\ cm)$$

$$M_0 = (3\times10^{11})(10^2)(dyne-cm)$$

$$M_0 = 3\times10^{13}\ dyne-cm$$

Again it is helpful to use scientific notation, since a dyne-cm is really a puny amount of moment.

Now let's consider a second case, the Sept. 12, 1994 Double Spring Flat earthquake, which occurred about 25 km southeast of Gardnerville. The first thing we have to do, since we're working in centimeters, is figure out how to convert the 15 kilometer length and 10 km depth of that fault to centimeters. We know that 100 thousand centimeters equal one kilometer, so we can write that equation and divide both sides by "km" to get a factor equal to one.

$$1\ km = 10^5\ cm \qquad 1 = \frac{10^5\ cm}{km}$$

Of course we can multiply anything by one without changing it, so we use it to cancel the kilometer units and put in the right centimeter units:

$$M_0 = (3\times10^{11}\ \frac{dyne}{\cancel{cm^2}})(10\ \cancel{km})\left[\frac{10^5\ \cancel{cm}}{\cancel{km}}\right](15\ \cancel{km})\left[\frac{10^5\ \cancel{cm}}{\cancel{km}}\right](30\ cm)$$

$$M_0 = 1.1\times10^{25}\ dyne-cm$$

Of course this result needs scientific notation even more desperately. We can see that this earthquake, the largest in Nevada in 28 years, had two times ten raised to the twelfth power, or 2 trillion, times as much moment as breaking the rock on the lab table.

There is a standard way to convert a seismic moment to a **magnitude**. The equation is:

$$M_w = \frac{2}{3}\left[\log_{10} M_0\ (dyne-cm) - 16.0\right]$$

Now let's use this equation (meant for energies expressed in dyne-cm units) to estimate the **magnitude** of the tiny earthquake we can make on a lab table:

$$M_0 = 3\times10^{13}\ dyne-cm$$

$$M_w = \frac{2}{3}\left[\log_{10}(3\times10^{13}\, dyne-cm) - 16.0\right]$$

$$M_w = \frac{2}{3}\left[\sim 13.5 - 16.0\right]$$

$$M_w \sim \frac{2}{3}(-2.5)$$

$$M_w \sim -1.7$$

Negative magnitudes are allowed on Richter's scale, although such earthquakes are certainly very small.

Next let's take the energy we found for the Double Spring Flat earthquake and estimate its magnitude:

$$M_0 = 1.4\times10^{25}$$

$$M_w = \frac{2}{3}\left[\log_{10}(1.4\times10^{25}\,dyne{-}cm) - 16.0\right]$$

$$M_w = \frac{2}{3}\left[\sim 25.2 - 16.0\right]$$

$$M_w \sim \frac{2}{3}(9.2)$$

$$M_w \sim 6.1$$

The magnitude 6.1 value we get is about equal to the magnitude reported by the UNR Seismological Lab, and by other observers.

Seismic Energy:

Both the magnitude and the seismic moment are related to the amount of energy that is radiated by an earthquake. Richter, working with **Dr. Beno Gutenberg,** early on developed a relationship between magnitude and energy. Their relationship is:

$$\log E_S = 11.8 + 1.5M$$

giving the energy E_S in **ergs** from the magnitude M. Note that E_S is not the total ``intrinsic" energy of the earthquake, transferred from sources such as gravitational energy or to sinks such as heat energy. It is only the amount radiated from the earthquake as seismic waves, which ought to be a small fraction of the total energy transfered during the earthquake process.

More recently, **Dr. Hiroo Kanamori** came up with a relationship between seismic moment and seismic wave energy. It gives:

$$Energy = (Moment)/20{,}000$$

For this moment is in units of dyne-cm, and energy is in units of ergs. dyne-cm and ergs are unit equivalents, but have different physical meaning.

Let's take a look at the seismic wave energy yielded by our two examples, in comparison to that of a number of earthquakes and other phenomena. For this we'll use a larger unit of energy, the seismic energy yield of quantities of the explosive TNT (We assume one ounce of TNT exploded below ground yields 640 million ergs of seismic wave energy):

Richter Magnitude	TNT for Seismic Energy Yield	Example (approximate)
-1.5	6 ounces	Breaking a rock on a lab table
1.0	30 pounds	Large Blast at a Construction Site
1.5	320 pounds	
2.0	1 ton	Large Quarry or Mine Blast
2.5	4.6 tons	
3.0	29 tons	

3.5	73 tons	
4.0	1,000 tons	Small Nuclear Weapon
4.5	5,100 tons	Average Tornado (total energy)
5.0	32,000 tons	
5.5	80,000 tons	Little Skull Mtn., NV Quake, 1992
6.0	1 million tons	Double Spring Flat, NV Quake, 1994
6.5	5 million tons	Northridge, CA Quake, 1994
7.0	32 million tons	Hyogo-Ken Nanbu, Japan Quake, 1995; Largest Thermonuc
7.5	160 million tons	Landers, CA Quake, 1992
8.0	1 billion tons	San Francisco, CA Quake, 1906
8.5	5 billion tons	Anchorage, AK Quake, 1964
9.0	32 billion tons	Chilean Quake, 1960
10.0	1 trillion tons	(San-Andreas type fault circling Earth)
12.0	160 trillion tons	(Fault Earth in half through center, OR Earth's daily receipt of solar energy)

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160 trillion tons of dynamite is a frightening yield of energy. Consider, however, that the Earth receives that amount in **sunlight** every day.

Practical ways of estimating magnitude

Most seismologists prefer to use the seismic moment to estimate earthquake magnitudes. Finding an earthquake fault's length, depth, and its slip can take several days, weeks, or even months after a big earthquake. Geologists' mapping of the earthquake's fault breaks, or seismologists' plotting of the spatial distribution of aftershocks, can give these parameters after a substantial effort. But some large earthquakes, and most small earthquakes, show neither surface fault breaks nor enough aftershocks to estimate magnitudes the way we have above. However, seismologists have developed ways to estimate the seismic moment directly from seismograms using computer processing methods. The Centroid Moment Tensor Project at Harvard University has been routinely estimating moments of large earthquakes around the world by seismogram inversion since 1982.

Another measure of an earthquake

Seismologists use a separate method to estimate the **effects** of an earthquake, called its **intensity**. **Intensity** should not be confused with **magnitude**. Although each earthquake has a single magnitude value, its effects will vary from place to place, and there will be many different intensity estimates. You can read about the Mercalli Intensity Scale, one popular way to characterize earthquake effects.

J. Louie, 9 Oct. 1996

Previous: Seismic Waves --- Next: Earthquake Effects in Kobe, Japan

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